ISSN 2521-0165
Volume 8, Special Issue 1, January 2026

JCBM

JOURNAL OF CONSTRUCTION BUSINESS & MANAGEMENT

SPECIAL EDITION

TABLE OF CONTENTS

Volume 8, Special Issue 1, January 2026

ABOUT JCBM

The **Journal of Construction Business and Management (JCBM)** is an open access journal published bi-annually by the University of Cape Town Libraries, South Africa. The Journal is hosted by the Construction Business and Management Research Group of the University of Cape Town. The journal aims to explore the experience of construction industry stakeholders and trends in the global system. It aims to publish peer reviewed and highly quality papers emanating from original theoretical based research, rigorous review of literature, conceptual papers and development of theories, case studies and practical notes. The journal also welcomes papers with diverse methodological research approaches including qualitative, quantitative, and mixed methods. Contributions are expected from academia, public administrators, professionals in the public sector and private practice (such as contracting organizations and consulting firms) and other related bodies and institutions (such as financial, legal and NGOs).

The scope of **Journal of Construction Business and Management (JCBM)** covers but is not limited to construction management and project delivery, strategic management, decision making, skills development, organizational practices and procedures in construction business. The specific areas in construction management, sustainability in construction and project delivery include project planning/feasibility studies, procurement, resource management, international construction, ethical issues, industrial relations, legislative requirements and regulations, construction education, information and communication technologies, housing policies, and urban design and development. Strategic management in construction covers risk management, quality management, resilience and disaster management, cultural and societal management, project life cycle management, and knowledge creation and management. Among issues in construction organizational practices and procedures covered are business development strategies, human resources and career development, continuous professional development, leadership systems, marketing strategies, gender issues and corporate social responsibility

Journal of Construction Business and Management (JCBM) is a peer reviewed journal. All research articles in this journal undergo rigorous peer review, based on initial editor and anonymised refereeing by at least two anonymous referees.

Journal of Construction Business and Management (JCBM) Partners:

University of Cape Town

Obafemi Awolowo University

The UCT Library takes no responsibility for the content published within journals that are hosted on OpenUCT: open journals and does not accept any liability arising out of the use of or the inability to use the information contained herein. The library, on behalf of itself and the University, assumes no responsibility, and shall not be liable for any breaches of agreement with other publishes/hosts.

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Advancing Multidisciplinary Approaches for Sustainable Construction and Project Management

Special Issue Editorial January 2026

Kehinde Temitope Alade
Federal University of Technology Akure, Nigeria
https://orcid.org/0000-0002-1644-2714

Justus Ngala Agumba
Tshwane University of Technology, South Africa
https://orcid.org/0000-0003-1077-1186

Introduction

The construction industry is undergoing a profound transformation driven by rapid advances in digital technologies, heightened sustainability imperatives, and increasing pressures for resilience, efficiency, and accountability. Across both developed and developing economies, these forces are reshaping how construction projects are conceived, delivered, and managed. Yet, the pace and nature of this transformation remain uneven, particularly in contexts characterised by institutional constraints, fragmented industry structures, and resource limitations. It is against this backdrop that this special issue of the *Journal of Construction Business and Management (JCBM)* was conceived.

Discussion of the Papers

This special issue, drawn from a selection of original and peer-reviewed articles from the 2025 CBPM conference, addresses contemporary challenges and innovations in construction business and project management. As Guest Editors, we are particularly pleased with the coherence and relevance of the contributions assembled in this issue. Collectively, the contributions address a growing need for empirically grounded, contextually sensitive research that advances both theory and practice, particularly in the Global South. The papers reflect JCBM's commitment to methodological diversity and intellectual rigour, drawing on quantitative, qualitative, and mixed-methods approaches to illuminate complex industry phenomena.

A central theme running through this issue is the role of digital and emerging technologies in enhancing construction performance. Several articles (Aju and Mokgohloa, 2026; Osundiran and Tshehla, 2026; Anugwo et al., 2026; Amiri and Saghatforoush, 2026) explore the adoption, integration, and impact of tools such as artificial intelligence, blockchain, Building Information Modelling (BIM), the Internet of Things, and smart building technologies. These studies do not merely commend technological potential; rather, they critically examine the barriers, risks, and organisational dynamics that shape technology uptake, especially in environments where regulatory uncertainty, skills gaps, and cost constraints are significant. In doing so, the authors offer nuanced insights into why technological transformation in construction often lags other sectors, and what can be done to address this challenge.

Equally prominent in this special issue are contributions (Moyo et al., 2026; Ngoy et al., 2026; Harinarain and Babalola, 2026) that address sustainability, resilience, and risk management. From renewable energy financing (Wamuziri, 2026) and sustainable building technologies (Ngoy et al., 2026) to infrastructure resilience and policy constraints (Abudu et al., 2026), the papers engage with pressing questions about how the construction sector can contribute to long-term socio-economic and environmental goals. Importantly, these discussions are grounded in real-world contexts across Africa (Ghana, Nigeria, South Africa, Zimbabwe) and other emerging economies, highlighting the interplay between global sustainability agendas and local institutional, economic, and cultural realities.

Beyond technology and sustainability, the issue also foregrounds critical business and management concerns (Aiyetan et al., 2026; Harinarain and Babalola, 2026; Osundiran and Tshehla,2026; Abudu et al., 2026 Moyo et al., 2026), including procurement practices, client influence, supply chain efficiency, and user satisfaction in the built environment. Together, these studies reinforce the view that construction performance is not determined solely by technical solutions, but by the alignment of organisational strategies, stakeholder relationships, and governance frameworks. While each article stands on its own merit, collectively they advance a shared conversation about how construction business and management research can better respond to contemporary industry challenges. The insights presented here will be of value to academics seeking to extend theoretical frontiers, policymakers aiming to craft enabling regulatory environments, and practitioners striving to improve project outcomes in increasingly complex settings.

Conclusion

We would like to express our sincere appreciation to the authors for their high-quality submissions and to the reviewers for their constructive and timely feedback, which has been instrumental in strengthening the papers. We are also grateful to the Editor-in-Chief, the editorial team, and the University of Cape Town Libraries for their support in bringing this special issue to fruition. It is our hope that this special issue will stimulate further research, dialogue, and collaboration across disciplines and regions, and that it will contribute meaningfully to the ongoing transformation of the construction industry toward greater innovation, sustainability, and resilience.

References

Abudu, H. D., Mewomo, C. M., Adjei, K. O., & Bondinuba, F. K. (2026). The Influence of Technical and Non-Technical Emergency Response Systems on Infrastructure Resilience. *Journal of Construction Business and Management*, *8*(S1), 30-47. https://doi.org/10.15641/jcbm.8.S1.1923

Aiyetan, A., Das, K. D., & Ayodabo, B. (2026). Factors Influencing Procurement in Construction: The Role of Clients and Construction Machinery in Kwazulu-Natal. *Journal of Construction Business and Management*, *8*(S1), 72-87. https://doi.org/10.15641/jcbm.8.S1.1930

Aju, O. G., & Mokgohloa, K. (2026). Leveraging Artificial Intelligence for Digital Transformation of Construction and Project Management Practices. *Journal of Construction Business and Management*, *8*(S1), 13-29.

https://doi.org/10.15641/jcbm.8.S1.1921

Amiri, M., & Saghatforoush, E. (2026). From Exploration to Prioritisation: Advancing BIM–Iot Integration for Construction Health and Safety Improvement. *Journal of Construction Business and Management*, *8*(S1), 125-139. https://doi.org/10.15641/jcbm.8.S1.1939

Anugwo, I. C., Appau, W. M., Attakora-Amaniampong, E., & Simpeh, F. (2026). Smart, but Not Spontaneous? Exploring the Satisfaction Gap and Drivers in Smart Lighting in Student Housing in Ghana. *Journal of Construction Business and Management*, *8*(S1), 88-98. https://doi.org/10.15641/jcbm.8.S1.1934

Harinarain, N., & Babalola, A. (2026). Constraining Sustainability: A Critical Examination of Construction Policy and Practice in Nigeria. *Journal of Construction Business and Management*, *8*(S1), 111-124. https://doi.org/10.15641/jcbm.8.S1.1938

Moyo, C., Moyo, T., & Mudombo, M. V. (2026). Integrating Sustainable Materials into Construction: A Review of Zimbabwe's Model Building By-Laws. *Journal of Construction Business and Management*, *8*(S1), 99-110. https://doi.org/10.15641/jcbm.8.S1.1936

Ngoy, K. S., Daweti, E., Molise, R., Chinasamy, D., & Windapo, A. (2026). Evaluation of Sustainable Building Technologies Adoption in Housing Construction Across Socio-Economic Contexts in Cape Town, South Africa. *Journal of Construction Business and Management*, *8*(S1), 140-154. https://doi.org/10.15641/jcbm.8.S1.1948

Osuizugbo, I. C., Okorafor, C., Awuzie, B. O., & Iyanda, V.O. (2026). An Exploratory Factor Analysis of Critical Barriers to Adopting Emerging Technologies for Quality Management in Construction Projects. *Journal of Construction Business and Management*, *8*(S1), 1-12. https://doi.org/10.15641/jcbm.8.S1.1910

Osundiran, A. O., & Tshehla, M. (2026). Port efficiency: The Application of Blockchain Technology in the Construction Material Supply Chain. *Journal of Construction Business and Management*, *8*(S1), 48-61. https://doi.org/10.15641/jcbm.8.S1.1924

Wamuziri, S. (2026). Risk Mitigation Strategies In Financing Renewable Energy Projects in Sub-Saharan Africa. *Journal of Construction Business and Management*, *8*(S1), 62-71. https://doi.org/10.15641/jcbm.8.S1.1929

ARTICLES

JCBM (2025) 8(S1) 1-12

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

An Exploratory Factor Analysis of Critical Barriers to Adopting Emerging Technologies for Quality Management in Construction Projects

Innocent Chigozie Osuizugbo[1], Chikezirim Okorafor[2], Bankole Osita Awuzie[3], and Victor Olukayode Iyanda[4]

[1&3]Department of Construction Management and Quantity Surveying, University of Johannesburg, Doorfontein Campus, Johannesburg, South Africa
[2]Department of Civil Engineering & Construction Studies Midland, Durban University of Technology Scottsville, South Africa
[4]Department of Building Technology, Bells University of Technology, Ota, Nigeria

Received 24 September 2025; received in revised form 10 December 2025, 25 December 2025, 25 December 2025; accepted 27 December 2025
https://doi.org/10.15641/jcbm.8.S1.1910

Abstract

This study aims to examine the barriers to the adoption of emerging technologies for quality management in construction projects. A questionnaire was designed to investigate the barriers to the adoption of emerging technologies for quality management in construction projects. Questionnaires were distributed, and 127 valid responses were elicited. Thereafter, data were analysed using descriptive and inferential statistics. The study was limited to barriers to the adoption of emerging technologies in construction quality management in Nigeria utilising a quantitative research method. The study's findings can serve as a model for tackling similar barriers in other countries in the global south. The results of the exploratory factor analysis reveal the critical barriers to the adoption of emerging technologies in construction quality management in the Nigerian construction industry can be grouped into three principal components: institutional and regulatory, organisational, and technology and industry collaboration. Understanding these findings provides a roadmap to accelerate the adoption of emerging technologies in construction quality management, leading to improved productivity, reduced rework, enhanced compliance, and sustainable industry growth.

Keywords: Adoption, Barriers, Construction projects, Emerging technologies, Quality management.

1. Introduction

The construction industry plays a significant role in a country's economic and national growth. However, the impact of this sector has been affected by productivity problems and poor project performance, as reported by Osuizugbo and Alabi (2021). Past studies have identified factors responsible for the poor construction project performance, including industry complexity, poor quality, safety issues, low productivity, slow innovation, high costs, client dissatisfaction, and skill shortages, among others (Osuizugbo & Ojelabi, 2020). Notably, poor-quality construction project delivery has been reported as the most challenging and prevalent issue within the construction industry (Luo *et al.*, 2022). Meanwhile, the sector's growth depends relatively on the quality of projects. Thus, effective management of construction projects' quality should be paramount to construction stakeholders. In other words, quality management is a key indicator which affects the value of construction projects.

More recent attention has focused on developing emerging technologies to enhance construction quality management and inspection, thereby improving the construction industry's image. Emerging technology in this study refers to innovative, cutting-edge advancements in the early stages of development that have the potential to impact society, industries, and economies significantly. Blockchain, Photogrammetry and laser scanning, Augmented Reality (AR), Building Information Modelling, Internet of Things (IoT), and

[1] Corresponding Author
Email address: innocento@uj.ac.za

Computer Vision (CV), among others, are some of the emerging technologies employed in construction quality management (Luo *et al.*, 2022; Safa *et al.*, 2015; Wang, 2008). These emerging technologies are designed to provide remarkable benefits to safety on site, quality, and productivity improvement. Adopting these emerging technologies in construction projects helps eliminate information barriers between design, prefabrication, and construction, enhances training, safety, and communication, reduces rework, enables process monitoring, preventive maintenance, site productivity assessment, real-time structural health tracking, and enhances defect detection and quality management (Luo *et al.*, 2019).

Despite many benefits that are linked with these digital tools, some challenges hinder its adoption and application in the construction sector which includes resistance to change, security concerns, high costs of hardware and software, absence of standardised guidelines and practices, lack of financial need, lack of market data for technology incorporation, and low level of knowledge among others (Tam *et al.,* 2024; Chen *et al.*, 2023; Maqsoom*et al.*, 2023; Kamaruddeen*et al.*, 2022). According to Saka and Chan (2019), the construction industry has been accused of lagging in the implementation of technology compared to other sectors. The common approach to assessing new policies and their implementation is to study the barriers/challenges they face, which typically requires identifying the root causes of resistance to change (Osuizugbo *et al.*, 2024). Using Nigeria as a representative case, these barriers are specifically significant because of economic constraints and poor quality in construction project delivery. These barriers to emerging technologies are intensified by a shortage of technical expertise and insufficient commitment to research and development, hindering the adoption of advanced quality management practices in construction projects. Secondly, high costs of software and hardware, and low knowledge of digital tools formed additional barriers. These barriers overlap with economic and regulatory factors: monetary limitations hinder the use of cutting-edge technologies, and regulatory guidelines may lack the necessary enforcement and incentives to drive the adoption and application of emerging technologies in construction quality management. Addressing these interconnected barriers is vital for enhancing the quality of construction projects in Nigeria and other nations in the global south.

Over time, several studies have been conducted on quality management. For instance, Keenan and Rostami (2019) examined the influence of quality management systems on construction performance. Wickramarachchi *et al.* (2018) studied total quality management execution in the Sri Lankan construction industry. In contrast, Wang and Wei (2020) investigated the implementation of BIM-based technology for quality management in construction engineering. Wang (2008) proposes Radio Frequency Identification (RFID)-based technology for enhancing construction quality inspection and management. The study by Safa *et al.* (2015) presented an automated approach to construction quality management that utilised advanced technologies to detect defects. The majority of these existing studies have primarily been conducted in the global North. Moreover, not all African countries have derived the same benefit from emerging technologies, including digitalisation processes (Badaru & Mphahlele, 2023). Thus, study that addresses barriers to the adoption of emerging technologies for quality management in construction projects in Nigeria are scarce. This implies that there is little to no understanding of the factors hindering the adoption of emerging technologies for quality management in construction projects in Nigeria. In addition, industry characteristics influence the adoption of emerging technologies for construction practices (Kamaruddeen *et al.*, 2022). This indicates that the adoption and application of emerging technologies for quality management practices may vary across countries. Hence, to tackle the identified gap in existing knowledge, this study aims to examine the barriers to the adoption of emerging technologies for quality management in construction projects in Nigeria.

The study's findings contributed to more effective quality management studies by highlighting critical barriers to the adoption of emerging technologies in construction quality management. An understanding of these barriers could aid construction practitioners, organisations, government, and policymakers in developing strategies to minimise them and promote the adoption of emerging technologies for quality management in the sector. Overcoming these barriers can improve efficiency, reduce costs and delays, and enhance build quality, thereby boosting investor confidence and supporting sustainable infrastructure. It can also drive job creation, strengthen local skills, attract foreign investment, and ultimately promote industry growth and economic development in Nigeria and other developing countries. While centred on the Nigerian context, the study's insights hold broader applicability and may guide practices in other countries with comparable socio-economic and cultural settings.

2. Literature Review

2.1. Theoretical Framework

This section explains the theoretical foundations that encourage the adoption of emerging technologies for quality management in construction. The theoretical framework offers a broad representation of the associations between elements within a particular subject. To deepen understanding of how emerging technologies for quality management in construction are adopted, the study draws on established theories. Specifically, the technology acceptance model seems to be appropriate.

2.1.1. Technology Acceptance Model

The technology acceptance model (TAM) is a widely used theory for exploring user acceptance behaviour, rooted in social psychology and drawing particularly on reasoned action theory (Ma & Liu, 2004). This theory explains how technology users come to accept and utilise technology, as shown in Figure 1 (Ma & Liu, 2004; Davis, 1989). TAM can be used to analyse the perceived usefulness and perceived ease of use of emerging technologies in construction quality management before their adoption by organisations or individuals (Davis, 1989). In the context of quality management in construction, emerging technologies such as quality management software, BIM, Blockchain, and Computer Vision often face resistance due to challenges in these areas (Tam *et al.,* 2024; Saka & Chan, 2019). For example, construction firms or workers may perceive these technologies as unnecessary or complex to use, resulting in low adoption rates. Factors such as security concerns, high costs of software and hardware, the absence of standardised guidelines and practices, and the lack of market data for technology incorporation, or low levels of knowledge and training, further compound this resistance, making it more difficult for the construction sector to take full benefit of emerging technologies.

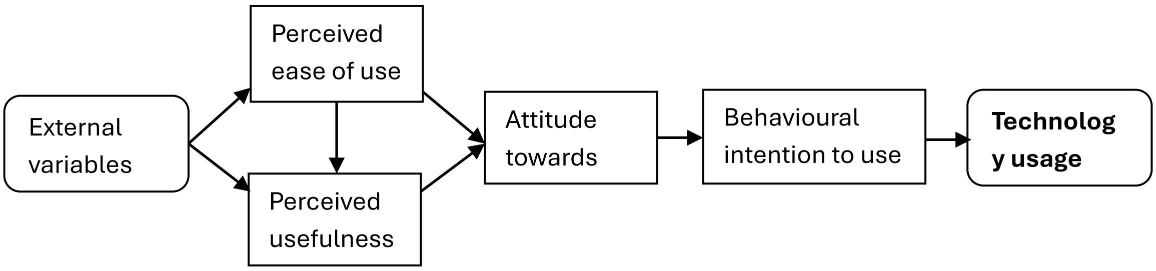

Figure 1: Technology acceptance model (Source: Ma & Liu, 2004)

Implications of the technology acceptance model for surmounting barriers to the adoption of emerging technologies in construction quality management are significant. Construction firms can develop approaches that encourage the adoption of emerging technology by tackling both perceived ease of use and usefulness. This may include better training and education programmes to demonstrate the advantages of emerging technologies for enhancing quality control, or simplifying the user interface to make digital tools more intuitive and user-friendly for construction practitioners. TAM highlights the role of organisational culture and leadership in promoting a positive attitude towards technological change (Ma & Liu, 2004; Davis, 1989). Thus, construction organisations can mitigate barriers to the adoption of emerging technologies and improve project management quality by clearly communicating long-term benefits and promoting innovation.

2.2. Barriers to Adoption of Emerging Technologies

Despite the significant advantages that emerging technologies offer for enhancing quality management in construction, their adoption remains constrained by various challenges. Recognising these obstacles is essential for practitioners, organisations, policymakers, and government bodies seeking to develop effective strategies for addressing them. Existing literature identifies a broad set of barriers, including resistance to change, data security concerns, high costs of software and hardware, a lack of standardised guidelines, limited financial resources, inadequate market information, and low levels of technical expertise, among others (Kamaruddeen *et al.*, 2022; Perera *et al.*, 2023; Maqsoom *et al.*, 2023; Chen *et al.*, 2023; Opoku *et al.*, 2023; Tam *et al.*, 2024). Although these findings highlight the complex and interconnected nature of adoption barriers, they are drawn mainly from studies in developed countries, where technological environments and support infrastructures are far more advanced.

In contrast, research emerging from African contexts, and Nigeria in particular, remains sparse, even though the benefits of digitalisation have not been evenly realised across the continent (Badaru & Mphahlele, 2023). This disparity indicates that barriers in developing countries may vary not only in scale but also in character. For instance, while cost and security concerns commonly feature in studies from developed countries, issues such as weak institutional frameworks, inadequate infrastructure, and low levels of awareness may exert a more significant influence in the Nigerian context (Azoro *et al.*, 2021; Iroha *et al.*, 2024; Oke *et al.*, 2025). Furthermore, the construction industry worldwide has been notably slow in adopting contemporary management practices (Parsamehr *et al.,* 2023). However, in Nigeria, this slow uptake is further exacerbated by limited investment in digital capabilities and a highly fragmented industry structure (Idowu *et al.*, 2023; Ibim & Dimkpa, 2025). Taken together, this highlights a notable gap in existing knowledge: although global studies discuss adoption barriers in broad terms, the specific contextual realities shaping these challenges in Nigeria remain insufficiently examined, underscoring the need for targeted research.

3. Research Methodology

The study used a quantitative research approach to determine the barriers to the adoption of emerging technologies for quality management in construction projects in Nigeria. This research approach elicits numerical data for analysis, ranking, or grouping (Creswell, 2014) and allows broad population insights within a short time (Daniel, 2016). Quantitative research relies on statistical analysis to draw conclusions and make predictions (Yilmaz, 2013), making it well-suited to this study's broad sampling approach. A literature review was conducted to identify barriers to the adoption of emerging technologies for quality management in construction. Relevant studies were located through searches in Scopus, Google Scholar, and Web of Science using keywords such as "construction," "quality management," "emerging technologies," and "barriers." Additional studies were identified through manual searches and citation tracking. Publications were included if they discussed factors that hindered the adoption or implementation of emerging technologies in construction or related sectors. Barrier-related information was manually extracted from each study. The resulting list of barriers was then used to develop the questionnaire to achieve the research objectives.

The questionnaire was utilised to gather data from survey participants regarding barriers to the adoption of emerging technologies for quality management in construction. The study used purposive sampling to select survey respondents. Purposive sampling is a non-probability approach that identifies participants based on characteristics relevant to the study objectives. The survey targeted key construction professionals, including builders, architects, electrical engineers, structural engineers, quantity surveyors, and mechanical engineers. A total of 209 respondents were selected to ensure representation across consulting, client, and contracting firms operating in construction projects in Nigeria. This approach ensured that the survey captured perspectives from professionals actively involved in the construction industry. The study considered Nigeria because the construction industry of Nigeria faces enormous challenges, including poor management, project delays, and poor quality control, among others, which may be a reason for the slow adoption of sustainable construction (Ogunmakinde *et al.*, 2019). These survey participants were selected due to their construction experience. A total of two hundred and nine (209) questionnaires were distributed to survey participants. After scrutinising the collected questionnaires, only 127 were useful, representing a 60.8% response rate. The respondents completed the questionnaire by providing feedback on barriers to the adoption of emerging technologies for quality management in construction, using a 5-point Likert scale. The scale ranged from 1 (not critical) to 5 (very critical), with 2 representing slightly critical, 3 representing moderately critical, and 4 representing critical. Data collection of this research commenced in May 2024 and was completed in July 2024. The statistical package for the social sciences analysed respondents' data using Cronbach's alpha, frequency distributions, percentages, mean scores, normalised mean analysis, and exploratory factor analysis. A reliability score of 0.904 exceeded the minimum threshold of 0.70 (Taherdoost, 2016), indicating strong internal consistency for the scale.

To identify the critical barriers to the adoption of emerging technologies in construction quality management, Normalised Mean Analysis (NMA) was employed. In this approach, the lowest mean score is standardised to 0 and the highest to 1, with all intermediate values proportionally transformed into decimal scores within this range, as illustrated in Equation 1 (Eq.1) (Munianday *et al.*, 2022; Xu *et al.*, 2010). Factors attaining a normalised mean value of 0.50 or above were classified as critical (Ayalp & Arslan, 2025).

$$\text{Normalised Mean Value} = \frac{\text{Mean} - \text{Minimum mean value}}{\text{Maximum mean value} - \text{Minimum mean value}} \ldots \text{Eq. (1)}$$

Exploratory Factor Analysis (EFA) was conducted to identify and cluster the critical barriers according to their underlying relationships. EFA enables the discovery of latent patterns in the dataset by examining inter-variable correlations without relying on predefined assumptions (Yong & Pearce, 2013). To assess the suitability of the data for factor analysis, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were applied. The KMO statistic assesses dataset adequacy by comparing the magnitude of observed correlations with those from partial correlations (Field, 2013), with values above 0.50 generally deemed acceptable for EFA (Norusis, 2008). Bartlett's test assesses whether the correlation matrix significantly diverges from an identity matrix, with high sphericity and low p-values confirming appropriateness for factor analysis (Pallant, 2020). Following confirmation of suitability, an oblique rotation (Oblimin with Kaiser Normalization) was applied because the factors were expected to be correlated, reflecting the interrelated nature of the barriers (Rajalahti & Kvalheim, 2011). This rotation method provides a more realistic representation of the relationships among constructs, thereby enhancing the interpretability of the factor structure (Osborne, 2015). Factors with eigenvalues greater than one were retained, while only those explaining a cumulative variance above 60% were considered valid to ensure construct reliability. Furthermore, factor loadings exceeding 0.50 were maintained, as they demonstrate substantial contributions to the constructs and facilitate meaningful interpretation (Osborne, 2015).

4. Findings and Discussion

4.1. Demographic Characteristics of Respondents

From the study, the majority of respondents involved in the survey are in the 31-40-year age bracket, representing 40.93% (52). This is followed by the age bracket 41-50 years, representing 37.8% (48); 21-30 years, representing 15.7% (20); and 51 years and above, representing 5.5% (7). This shows that the survey participants are mature enough to be involved in the research. Based on the respondents' professional background, builders are 54 (42.5%), followed by architects with 28 (22%), quantity surveyors with 20 (15.7%), electrical engineers with 12 (9.4%), structural engineers with 9 (7.1%), and mechanical engineers with 4 (3.1%). For the academic qualification of the respondents, 46.5% of the study population were bachelor's degree holders, followed by postgraduate diploma holders with 30.7%, master's degree holders with 13.4%, higher national diploma holders with 5.5%, and doctorate holders with 3.9%. For work experience, 11-15 years and 16-20 years have the same number of participants with 40 (31.5%), 21 years and above have 27 (21.3%), 6-10 years have 17 (13.4%), and 1-5 years experience have 3 (2.4%). These results confirmed the respondent's eligibility to be involved in the research. Furthermore, the consulting, contracting, and client firms have 62 (48.8%), 62 (48.8%), and 3 (2.4%), respectively.

4.2. Results of Normalised Mean Analysis

Table 1 presents the results of the NMA. Nine (9) barriers have normalised mean values (NMV) greater than 0.50, indicating their criticality as barriers to emerging technologies in construction quality management. As a result, nine (9) barriers can be considered critical barriers to emerging technologies in construction quality management, namely; Regulatory and legal challenges (TB2), Uncertain return on investment (ROI) (TB5), Integration Issues (TB3), Complexity (TB6), Resistance to change (TB4), Cost (high costs of software and hardware) (TB1), Technology availability (TB11), Limited industry collaboration and standards (TB15), and Risk of technology obsolescence (TB9).

4.3. Results of Exploratory Factor Analysis

The adequacy of the sample for exploratory factor analysis (EFA) was established using the ratio of sample size to the number of variables, yielding a ratio of 14.1 for the critical barriers, which exceeds the recommended minimum of 5.0. This confirms that the sample size was sufficient for EFA. Further validation was provided by the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, which recorded a value of 0.708, above the accepted threshold of 0.60, alongside Bartlett's test of sphericity ($\chi^2 = 623.846$, $p < 0.000$), indicating that the correlation matrix was significant and not an identity matrix (see Table 2). Together, these results demonstrate the dataset's

Table 1: Results of NMA on barriers to emerging technologies in construction quality management

Code	Barriers	Mean	Standard Deviation	NMV
TB1	Cost (high costs of software and hardware)	4.13	0.845	1.00*
TB2	Regulatory and legal challenges	3.69	0.842	0.56*
TB3	Integration Issues	3.74	0.819	0.61*
TB4	Resistance to change	3.98	1.035	0.85*
TB5	Uncertain return on investment (ROI)	3.79	1.094	0.66*
TB6	Complexity	3.67	1.016	0.54*
TB7	Lack of awareness (low level of knowledge)	3.33	1.099	0.19
TB8	Data security concerns	3.35	1.217	0.21
TB9	Risk of technology obsolescence	3.91	0.979	0.78*
TB10	Industry fragmentation	3.46	1.010	0.32
TB11	Technology availability	3.78	0.916	0.65*
TB12	Dependency on technology providers	3.16	1.130	0.02
TB13	Limited resources	3.14	1.283	0.00
TB14	Skills gap	3.35	1.257	0.21
TB15	Limited industry collaboration and standards	3.67	1.106	0.54*
TB16	Overreliance on technology	3.39	0.909	0.25

Note: NMV = Normalised Mean Value
* = Critical barriers

Table 2: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.708
Bartlett's Test of Sphericity	Approx. Chi-Square	623.846
	Df	36
	Sig.	0.000

suitability for factor analysis. The Scree plot (Figure 1) suggested the extraction of three components, guided by the ‘elbow’ point on the curve. The first component explained more variance than the combined variance of the remaining components, while the second and third components were distinctly separated, underlining their individual contributions.

Regarding factor loadings, values between 0.30 and 0.40 are generally considered the minimum threshold for practical significance (Ho, 2013). In this study, a cut-off of 0.30 was applied, and only loadings above this value were retained. Although a minimum loading threshold of 0.30 was adopted per established guidelines, the actual loadings observed in this study were substantially higher. Most items loaded strongly onto their respective components, with observed loadings generally exceeding 0.50. This indicates robust relationships between the variables and the extracted components, further supporting the reliability of the factor structure. Communalities ranged between 0.54 and 0.87, which are acceptable and indicate low to high levels of shared variance, thereby supporting the reliability of the extracted constructs (Costello and Osborne, 2005). As presented in Table 3, the first three critical barriers to emerging technologies in construction quality management recorded eigenvalues greater than 1 (4.253, 1.373, and 1.038), meeting the criterion for factor retention. Collectively, these three components explained 74.04% of the total variance, surpassing the recommended 60% threshold for construct adequacy (Ghosh and Jimtanapakamont,

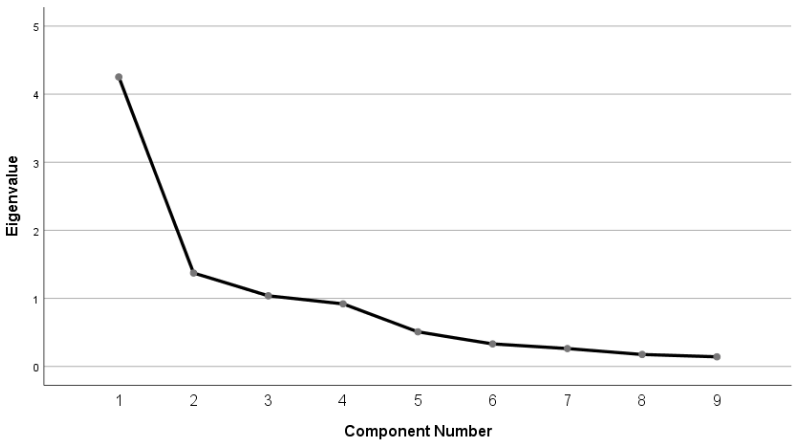

Figure 1: Scree plot

Table 3: The total variance explained by the critical barriers to emerging technologies in construction quality management

Critical Barriers	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings[a]
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
TB1	4.253	47.254	47.254	4.253	47.254	47.254	2.726
TB2	1.373	15.252	62.505	1.373	15.252	62.505	2.540
TB3	1.038	11.532	74.038	1.038	11.532	74.038	3.160
TB4	.919	10.214	84.252				
TB5	.508	5.649	89.901				
TB6	.331	3.674	93.574				
TB9	.262	2.915	96.489				
TB11	.175	1.947	98.436				
TB15	.141	1.564	100.000				

Extraction Method: Principal Component Analysis.

[a]When components are correlated, sums of squared loadings cannot be added to obtain a total variance.

2004). The rotated factor matrix is presented in Table 4.

Table 4: The factor matrix after rotation

Code	Critical barriers to emerging technologies in construction quality management	Extracted Communalities	Component		
			1	2	3
Component 1: Institutional and regulatory barrier					
TB2	Regulatory and legal challenges	0.767	0.765		
TB5	Uncertain return on investment (ROI)	0.744	0.741		
TB3	Integration Issues	0.539	0.708		
Component 2: Organisational barrier					
TB6	Complexity	0.794		0.845	
TB4	Resistance to change	0.732		0.747	
TB1	Cost (high costs of software and hardware)	0.579		0.636	
Component 3: Technology and industry collaboration barrier					
TB11	Technology availability	0.836			0.912
TB15	Limited industry collaboration and standards	0.872			0.794
TB9	Risk of technology obsolescence	0.801			0.723

Extraction Method: Principal Component Analysis
Rotation Method: Oblimin with Kaiser Normalization
Rotation converged in 14 iterations

4.4. Discussion on Key Findings

This part of the paper discusses the three underlying constructs (i.e. institutional and regulatory, organisational, and technology and industry collaboration barriers) hindering the adoption of emerging technologies in construction quality management and their critical barriers. To enhance clarity, the relationship between individual items and the factor labels was examined based on both statistical loadings and conceptual alignment. Items were assigned to factors not solely based on loading strength, but because their underlying meanings reflected shared thematic constructs identified in prior literature. For example, the item "integration issues" was grouped under Institutional/Regulatory barriers because the integration challenges reported by respondents largely arise from external systemic constraints, such as the absence of unified digital standards, lack of regulatory frameworks, and poor inter-organisational coordination, rather than from technical limitations within firms. Similarly, items loading on the Organisational and Technical factors reflect internal capabilities, resources, and operational practices within construction firms. This combined statistical–conceptual approach ensures that factor labels accurately represent the nature of the grouped barriers.

4.4.1. Institutional and Regulatory Barriers

Institutional and regulatory barriers emerged as the strongest underlying construct, explaining 47.25% of the total variance (see Table 3). This factor comprises three key items: (1) regulatory and legal challenges, (2) uncertain return on investment, and (3) integration issues. These findings align with evidence from other developing contexts such as Ghana and Malaysia (Pittri *et al.*, 2025; Thirumal *et al.*, 2024; Yap *et al.*, 2022). Collectively, these items indicate that macro-level institutional constraints, such as weak regulatory frameworks, unclear digital requirements, and fragmented integration standards, significantly shape firms' perceptions of risk and value when considering emerging technologies for quality management. Uncertain return on investment (ROI) further discourages organisations from committing resources to technologies whose long-term benefits remain ambiguous (Hassan *et al.*, 2024; Struckell *et al.*, 2022). Integration challenges compound these issues, particularly in environments where legacy systems, siloed vendor solutions, and the absence of common data standards inhibit seamless technology adoption (Whyte *et al.*, 2022; Basiru *et al.*, 2022).

Interpreted through the TAM, these barriers predominantly affect perceived usefulness and perceived ease of use. First, regulatory uncertainty and unpredictable ROI weaken perceived usefulness by reducing organisational confidence that technology adoption will lead to tangible performance improvements. Second, integration issues increase perceived complexity, thereby lowering perceived ease of use. Together, these effects diminish behavioural intention to adopt emerging technologies, consistent with TAM's premise that perceived usefulness and perceived ease of use are primary determinants of adoption decisions.

These findings underscore the need for stronger institutional support mechanisms to enhance technology uptake in Nigeria's construction sector. Policymakers and regulators should establish clear digital standards, procurement guidelines, and liability frameworks to reduce legal ambiguity and foster greater interoperability across systems. Incentives or supportive financing schemes may also help mitigate firms' concerns about ROI. Strengthening these institutional conditions would enhance both perceived usefulness and perceived ease of use, ultimately improving industry-wide adoption intentions and contributing to more effective digital integration in quality management practices.

4.4.2. Organisational Barriers

Organisational barriers emerged as the second underlying construct, explaining an additional 15.25% of the variance, bringing the cumulative explained variance to 62.51% (see **Table 3**). This factor captures internal organisational constraints that hinder the adoption of emerging technologies, including technological complexity, workforce resistance to change, and high implementation costs. Similar findings have been reported in India and Vietnam (Tam *et al.*, 2024; Ramanna *et al.*, 2024; Thirumal *et al.*, 2024; Luo *et al.*, 2022). Complex technologies typically require specialised skills, extensive training, and significant workflow adjustments, demands that can overwhelm firms with limited technical capacity. Resistance to change also plays a substantial role, as employees may view new digital systems as disruptive or threatening to their established work practices. Furthermore, the high costs of acquiring, integrating, and maintaining advanced digital tools pose significant financial constraints, particularly for firms operating in developing economies, where profit margins and investment capital are limited (Ajiga *et al.*, 2024).

When interpreted through TAM, these organisational barriers primarily affect perceived ease of use and perceived usefulness. Technological complexity and employee resistance reduce perceived ease of use by increasing expectations of difficulty, training burden, and workflow disruption. High costs and uncertain short-term benefits weaken perceived usefulness, as firms question whether the expected performance improvements justify the financial and organisational investment required. Together, these effects diminish behavioural intention, thereby slowing or preventing actual adoption.

To address these organisational barriers, construction firms should implement structured change-management strategies, including early employee involvement, targeted training programmes, and clear communication of expected benefits. Staged or incremental investment approaches can help reduce financial pressure and allow organisations to build capacity gradually. Generating early, visible benefits, such as reductions in rework, faster inspections, or improved documentation quality, can strengthen perceived usefulness and perceived ease of use among employees, reinforcing TAM's causal pathways and accelerating adoption. Policymakers and industry associations may also play a supporting role by offering subsidised training or sharing best practices to enhance organisational readiness.

4.4.3. Technology and Industry Collaboration Barriers

Technology and industry collaboration barriers emerged as the third underlying construct, contributing an additional 11.53% of the variance, and raising the total cumulative variance explained by the three components to 74.04% (see **Table 3**). This factor comprises issues related to technology availability, lack of industry-wide collaboration and standards, and fears of technological obsolescence. Similar patterns have been identified in previous studies (Pittri *et al.*, 2025; Tam *et al.*, 2024; Luo *et al.*, 2022; Yap *et al.*, 2022). Limited access to appropriate digital tools restricts firms' ability to explore and implement innovations, particularly in environments with weak digital infrastructure (Pittri *et al.*, 2025). The absence of shared standards and collaborative frameworks intensifies fragmentation, leading to compatibility issues and slow diffusion across the sector (Kelvin & Aliu, 2025; Soltani *et al.*, 2025). Additionally, the rapid pace of technological development heightens fears of obsolescence, discouraging firms from investing in solutions that may quickly lose relevance (Păvăloaia & Necula, 2023; Cascio & Montealegre, 2016). These barriers demonstrate that adoption is influenced not only by internal organisational readiness but also by the broader technological ecosystem and the level of collaboration within the industry.

Using the TAM framework, these barriers primarily impact perceived usefulness and behavioural intention. Concerns about obsolescence and interoperability diminish perceived usefulness by reducing confidence that the technology will deliver sustained value over time. Limited industry collaboration and the absence of standardised practices undermine behavioural intention by introducing uncertainty about future compatibility, vendor support, and long-term viability. Organisations become hesitant to adopt technologies that lack clear industry endorsement or stable integration pathways.

These findings highlight the importance of strengthened industry collaboration, coordinated standard-setting, and reliable vendor support systems. Industry associations, regulatory agencies, and technology providers should work together to establish interoperability standards, promote joint testing and pilot initiatives, and ensure long-term support for key technologies. Such collaborative efforts can improve the reliability and compatibility of emerging technologies, thereby increasing perceived usefulness and reducing adoption hesitancy. By enhancing the industry-wide environment, stakeholders can reinforce TAM's predictive mechanisms and accelerate the diffusion of technology in construction quality management.

Taken together, the three underlying constructs, institutional and regulatory barriers, organisational barriers, and technology and industry collaboration barriers, demonstrate that a combination of macro-level institutional conditions, firm-level readiness, and sector-wide technological dynamics shapes the adoption of emerging technologies in construction quality management. When interpreted through the Technology Acceptance Model, these barriers collectively weaken perceived usefulness**,** perceived ease of use, and ultimately behavioural intention, illustrating that the challenges to digital adoption are interconnected rather than isolated. Strengthening regulatory clarity, enhancing organisational capacity, and improving technological interoperability across the industry are therefore essential strategies for improving perceptions of value and usability. Addressing these multi-level constraints can create a more enabling environment for technology uptake, reinforcing TAM's relevance in explaining adoption behaviour within the construction sector and supporting more effective digital transformation in quality management practices.

5. Conclusion and Further Research

This study provides empirical evidence on the barriers hindering the adoption of emerging technologies for construction quality management in Nigeria. In this context, integration remains significantly slower than in the Global North. Using data from 127 practitioners and applying exploratory factor analysis, the study establishes a three-factor structure: institutional and regulatory barriers, organisational barriers, and technology and industry collaboration barriers, that collectively explain the significant constraints to adoption. This factor structure represents the study's core contribution, offering a systematic framework for understanding how fragmented regulations, organisational readiness gaps, and weak technological ecosystems jointly impede the diffusion of technology in developing-country construction sectors.

The findings add new insights to the literature on the Global South by showing how regulatory uncertainty, low industry collaboration, and technology obsolescence risks are especially pronounced in Nigeria's construction environment, where digital infrastructure is weaker, and investment capacity is limited. These contextual nuances help explain why adoption patterns diverge from those typically reported in high-income countries.

Based on the three-factor structure, the study offers three practical recommendations. First, policymakers should strengthen and harmonise regulatory and standards frameworks to reduce uncertainty and improve interoperability across firms. Second, construction organisations should invest in structured change management, training, and phased implementation strategies to address internal resistance and complexity. Third, industry associations and technology vendors should collaborate to build shared digital platforms, standards, and support systems, lowering costs and mitigating fears of obsolescence. These actions collectively target the key barriers identified by the model.

The study is not without limitations. It focuses on Nigerian practitioners and relies solely on quantitative survey data, which may not fully capture deeper institutional or cultural dynamics. Additionally, TAM was used only as an interpretive lens rather than being empirically operationalised. Future research should integrate qualitative methods, undertake comparative case studies across regions, and directly measure TAM constructs such as perceived usefulness and behavioural intention to provide stronger empirical validation of adoption pathways in construction quality management.

References

Ajiga, D., Okeleke, P.A., Folorunsho, S.O. & Ezeigweneme, C. (2024), 'The role of software automation in improving industrial operations and efficiency', *International Journal of Engineering Research Updates*, 07(01), pp. 022–035. https://doi.org/10.53430/ijeru.2024.7.1.0031

Ayalp, G.G., & Arslan, F. (2025). Modeling Critical Rework Factors in the Construction Industry: Insights and Solutions. *Buildings*, 15(4), 606. https://doi.org/10.3390/buildings15040606

Azoro, C.J.S. , Onah, C.A. & Agulefo, Q.O. (2021), "Weak Institutions and Poor Governance in Nigeria: A Socio-Legal Perspective", *African Journal of Law, Political Research and Administration*, 4(2), pp. 61-70. DOI: 10.52589/AJLPRA-5IUFPPRU

Badaru, K.A. & Mphahlele, R.S. (2023), 'Effects of Emerging Technologies on African Development: A Narrative Review on Selected African Countries', *Research in Social Sciences and Technology* 8(3), pp. 36-51.

Basiru, J.O., Ejiofor, C.L., Ornukwulu, E.C. & Attah, R.U. (2022), 'Streamlining procurement processes in engineering and construction companies: A comparative analysis of best practices', *Magna Scientia Advanced Research and Reviews*, 6(1), pp. 118-135. DOI: 10.30574/msarr.2022.6.1.0073

Cascio, W.F. & Montealegre, R. (2016), 'How Technology Is Changing Work and Organizations', *Annual Review of Organizational Psychology and Organizational Behavior*, 3(1), pp. 349-375. DOI: 10.1146/annurev-orgpsych-041015-062352

Chen, X., Chang-Richards, A.Y., Yiu, T.W., Ling, F.Y.Y., Pelosi, A. & Yang, N. (2023), 'A multivariate regression analysis of barriers to digital technologies adoption in the construction industry', *Engineering, Construction and Architectural Management*, DOI 10.1108/ECAM-11-2022-1051.

Creswell, J. (2014), *Research design – qualitative, quantitative, and mixed method approaches*, 4th ed. CA: SAGE Publications Inc.

Daniel, E. (2016), 'The Usefulness of Qualitative and Quantitative Approaches and Methods in Researching Problem-Solving Ability in Science Education Curriculum', *Journal of Education and Practice*, 7(15), pp. 91-100.

Davis, F. (1989), 'Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology', *MIS Quarterly*, 13, 319-340. https://doi.org/10.2307/249008

Field, A. (2013), *Discovering statistics using IBM SPSS statistics*. Sage publications

Ghosh, S., & Jintanapakanont, J. (2004). Identifying and assessing the critical risk factors in an underground rail project in Thailand: a factor analysis approach. *International journal of project management*, *22*(8), 633-643.

Hassan, A.M., Negash, Y.T. & Hanum, F. (2024), 'An assessment of barriers to digital transformation in circular Construction: An application of stakeholder theory', *Ain Shams Engineering Journal*, 15(7), 102787. https://doi.org/10.1016/j.asej.2024.102787.

Ho, R. (2013). *Handbook of univariate and multivariate data analysis with IBM SPSS*. CRC press. https://doi.org/10.1201/b15605

Ibim, A.A. and Dimkpa, K. (2025), "Nigerian Construction Industry Reforms and Private Sector Involvement: X-raying Cost Engineering Roles in Sustainable Infrastructure Procurement", *Journal of Evrimata: Engineering and Physics,* 3(1), pp. 170 – 178.

Idowu, A.O., Aigbavboa, C. and Oke, A.E. (2023), "Barriers to Digitalization in the Nigerian Construction Industry", *In: 2023 European Conference on Computing in Construction 40th International CIB W78 Conference,* Heraklion, Crete, Greece, July 10-12, 2023.

Iroha, E. V., Watanabe, T. & Satoshi, T. (2024), "Flawed Institutional Structures: Project Managers Underutilized in Nigeria's Construction Industry", *Buildings*, 14(3), 807. https://doi.org/10.3390/buildings14030807

Kamaruddeen, A.M., Rui, L.S., Lee, K.L., Alzoubi, H.M. &Alshurideh, M.T. (2022), 'Determinants of Emerging Technology Adoption for Safety Among Construction Businesses', *Academy of Strategic Management Journal,* 21(S4), pp. 1- 19.

Keenan, M. & Rostami, A. (2019), 'The impact of quality management systems on construction performance in the North West of England', *International Journal of Construction Management*, DOI: 10.1080/15623599.2019.1590974.

Kelvin, I.M. & Aliu, J.O. (2025), 'Bridging the digital divide: strategies for successful technology implementation in the UK construction sector', *International Journal of Construction Management*, https://doi.org/10.1080/15623599.2025.2541721

Luo, X., Li, H., Wang, H., Wu, Z., Dai, F. and Cao, D. (2019), "Vision-based detection and visualization of dynamic workspaces", *Automation in Construction*, 104, pp. 1–13. https://doi.org/10.1016/j.autcon.2019.04.001.

Luo, H., Lin, L., Chen, K., Antwi-Afari, M.F. & Chen, L. (2022), 'Digital technology for quality management in construction: A review and future research directions', *Developments in the Built Environment,* 12, 100087. https://doi.org/10.1016/j.dibe.2022.100087.

Ma, Q. & Liu, L. (2004), 'The Technology Acceptance Model: A Meta-Analysis of Empirical Findings', *Journal of Organizational and End User Computing,* 16(1), pp. 59-72.

Maqsoom, A., Zulqarnain, M., Irfan, M., Ullah, F., Alqahtani, F.K. & Khan, K.I.A. (2023), 'Drivers of, and Barriers to, the Adoption of Mixed Reality in the Construction Industry of Developing Countries', *Buildings*, 13, 872.

Munianday, P., Radzi, A. R., Esa, M., & Rahman, R. A. (2022), 'Optimal strategies for improving organizational BIM capabilities: PLS-SEM approach', *Journal of management in engineering*, *38*(3), 04022015.

Norusis, M. (2008), *SPSS 16.0 advanced statistical procedures companion*, Prentice Hall Press.

Ogunmakinde, O.E., Sher, W. & Maund, K. (2019), 'Challenges of the Nigerian construction industry: A systematic review'. *In: Conference: iiSBE Forum of Young Researchers in Sustainable Building*, 195-204, July, 2019, Prague, Czech Republic.

Oke, A.E., Aliu, J., Akinpelu, T.M., Ilesanmi, O.O. & Alade, K.T. (2025), "Breaking barriers: Unearthing the hindrances to embracing energy economics principles in Nigerian building projects", *Energy and Built Environment*, 6(3), pp. 534-544. https://doi.org/10.1016/j.enbenv.2024.01.011.

Opoku, D.-G.J., Perera, S., Osei-Kyei, R., Rashidi, M., Bamdad, K. and Famakinwa, T. (2023). 'Barriers to the Adoption of Digital Twin in the Construction Industry: A Literature Review'. *Informatics*, 10(14). https://doi.org/10.3390/informatics10010014

Osborne, J. W. (2015), 'What is rotating in exploratory factor analysis?' *Practical assessment, research, and evaluation*, *20*(2), pp. 1-8.

Osuizugbo, I. C. & Alabi, A. S. (2021), 'Built Environment Professionals' Perceptions of the Application of Artificial Intelligence in Construction Industry', *Covenant Journal of Research in the Built Environment,* 9(2), pp. 48-66.

Osuizugbo, I. C. & Ojelabi, A.R. (2020), 'Building Production Management Practice in the Construction Industry in Nigeria',*Engineering Management in Production and Services*, 12(2), pp.56-73.

Osuizugbo, I. C., Omer, M. M., Rahman, R. A., & Oshodi, O. S. (2024). A systematic search and review of early contractor involvement in construction project development. *Built Environment Project and Asset Management*, *14*(6), 835-857.

Pallant, J. (2020), *SPSS survival manual: A step by step guide to data analysis using IBM SPSS*. Routledge.

Parsamehr, M., Perera, U.S., Dodanwala, T.C., Perera, P. and Ruparathna, R. (2023), "A review of construction management challenges and BIM-based solutions: perspectives from the schedule, cost, quality, and safety management", *Asian Journal of Civil Engineering*, 24(1), pp.353-389. https://doi.org/10.1007/s42107-022-00501-4

Păvăloaia, V.-D., & Necula, S.-C. (2023), 'Artificial Intelligence as a Disruptive Technology—A Systematic Literature Review', *Electronics*, *12*(5), 1102. https://doi.org/10.3390/electronics12051102

Perera, S., Jin, X., Samaratunga, M. and Gunasekara, K. (2023), "Drivers and barriers to digitalisation: a cross-analysis of the views of designers and builders in the construction industry", *Journal of Information Technology in Construction (ITcon),* 28, pg. 87-106, DOI: 10.36680/j.itcon.2023.005.

Pittri, H., Godawatte, G. A. G. R., Esangbedo, O. P., Antwi-Afari, P., & Bao, Z. (2025), 'Exploring Barriers to the Adoption of Digital Technologies for Circular Economy Practices in the Construction Industry in Developing Countries: A Case of Ghana', *Buildings*, *15*(7), 1090. https://doi.org/10.3390/buildings15071090

Rajalahti, T., & Kvalheim, O.M. (2011). 'Multivariate data analysis in pharmaceutics: A tutorial review. *International Journal of Pharmaceutics*, 417(1–2), pp. 280-290. https://doi.org/10.1016/j.ijpharm.2011.02.019.

Ramanna, T.R., Venkatesh, M.P. & Manohar, G. (2024), 'Critical Barriers to Sustainable Construction Technology Adoption in Developing Countries – A Case Study in India', *International Research Journal on Advanced Engineering Hub,* 2(2), pp. 271-286.

Safa, M., Shahi, A., Nahangi, M., Haas, C. & Noori, H. (2015), 'Automating measurement process to improve quality management for piping fabrication', *Structures* 3, pp. 71–80. DOI: 10.1016/j.istruc.2015.03.003

Saka, A.B. & Chan, D.W.M. (2019), 'A Scientometric Review and Metasynthesis of Building Information Modelling (BIM) Research in Africa', *Buildings*, https://doi:10.3390/buildings9040085.

Soltani, S., Abbasnejad, B., Gu, N., Yu, R. & Maxwell, D. A. (2025), 'Multi-Faceted Analysis of Enablers and Barriers of Industrialised Building: Global Insights for the Australian Context', *Buildings*, 15, 214. https://doi.org/10.3390/buildings15020214.

Struckell, E., Ojha, D., Patel, P.C. & Dhir, A. (2022), 'Strategic choice in times of stagnant growth and uncertainty: An institutional theory and organizational change perspective', *Technological Forecasting and Social Change*, 182, 121839, https://doi.org/10.1016/j.techfore.2022.121839.

Taherdoost, H. (2016), 'Validity and reliability of the research instrument; how to test the validation of a questionnaire/survey in a research', *International Journal of Academic Research in Management*, 5(3), pp. 28-36.

Tam, N.V., Toan, N.Q. & Phong, V.V. (2024), 'Investigating potential barriers to construction digitalization in emerging economies: A study in Vietnam', *International Journal of Information Management Data Insights*, 4(1), 100226. https://doi.org/10.1016/j.jjimei.2024.100226.

Thirumal, S., Udawatta, N., Karunasena, G., & Al-Ameri, R. (2024), 'Barriers to Adopting Digital

Technologies to Implement Circular Economy Practices in the Construction Industry: A Systematic Literature Review', *Sustainability*, *16*(8), 3185. https://doi.org/10.3390/su16083185

Wang, L.C. (2008), 'Enhancing construction quality inspection and management using RFID technology', *Automation in Construction*, 17(4), pp. 467–479.

Wang, J. Z. & Wei, G. A. (2020), 'BIM-based Technology Implementation on Quality Management in Construction Engineering', *Journal of Physics: Conference Series IOP Publishing*, doi:10.1088/1742-6596/1601/4/042043.

Whyte, J., Davies, A. & Sexton, C. (2022), 'Systems integration in infrastructure projects: seven lessons from Crossrail', *Proceedings of the Institution of Civil Engineers - Management, Procurement and Law,* 175(3), pp. 103–109. https://doi.org/10.1680/jmapl.21.00014

Wickramarachchi, H.R., Sandanayake, Y.G. & Ekanayake, B. J. (2018), 'Total quality management implementation in Sri Lankan construction industry : A study of small and medium sized enterprises', *Proceed title: MERCon 2018 - 4th International Multidisciplinary Moratuwa Engineering Research Conference,* pp.19-24. DOI: 10.1109/MERCon.2018.8421946

Xu, Y., Yeung, J. F., Chan, A. P., Chan, D. W., Wang, S. Q., & Ke, Y. (2010), 'Developing a risk assessment model for PPP projects in China—A fuzzy synthetic evaluation approach', *Automation in Construction*, *19*(7), pp. 929-943.

Yap, J.B.H., Lam, C.G.Y., Skitmore, M. & Talebian, N. (2022), 'Alebian Barriers to the Adoption of New Safety Technologies in Construction: A Developing Country Context', *Journal of Civil Engineering and Management,* 28(2), pp. 120-133. https://doi.org/10.3846/jcem.2022.16014

Yilmaz, K. (2013), 'Comparison of quantitative and qualitative research traditions: epistemological, theoretical, and methodological differences', *European Journal of Education*, 48(2), pp. 311-325.

Yong, A. G., & Pearce, S. (2013), 'A beginner's guide to factor analysis: Focusing on exploratory factor analysis', *Tutorials in quantitative methods for psychology*, 9(2), pp. 79-94.

JCBM (2025) 8(S1) 13-29

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Leveraging Artificial Intelligence for Digital Transformation of Construction and Project Management Practices

Omojokun Gabriel Aju[1] and Kgabo Mokgohloa[2]

[1&2]Graduate School of Business Leadership, University of South Africa, South Africa

Received 02 October 2025; received in revised form 16 October 2025, 18 December 2025; accepted 27 December 2025
https://doi.org/10.15641/jcbm.8.S1.1921

Abstract

The construction and project management (CPM) sector is increasingly leveraging Artificial Intelligence (AI) to enhance efficiency, decision-making, and risk management. Despite its potential, AI adoption in CPM faces challenges, including fragmented implementation, workforce-readiness gaps, and concerns about governance and data security. This study conducts a systematic literature review (SLR) of peer-reviewed articles, industry reports, and grey literature from 2018 to 2025. The review identifies key thematic dimensions, including AI application areas, impacts on efficiency, cost, and time management, and adoption challenges related to governance, digital infrastructure, stakeholder engagement, workforce capacity, and ethical considerations. Drawing on these insights, a comprehensive implementation strategy is proposed that integrates technical, organisational, and ethical perspectives to support effective AI integration in CPM. This study advances knowledge by conceptualising an AI-integrated CPM ecosystem and proposing an evidence-based strategic implementation framework that bridges theoretical discourse and industry practice. The primary limitation is the lack of empirical validation of the proposed strategy through local case studies or pilot implementations, which are recommended to assess its practical applicability across diverse project contexts.

Keywords: Artificial Intelligence, Construction, Implementation Strategy, Project Management, Systematic Literature Review.

1. Introduction

The construction and project management sectors, traditionally characterised by labour-intensive processes and fragmented workflows, are undergoing a profound transformation driven by advancements in digital technologies. Among these technologies, artificial intelligence (AI) has emerged as a pivotal force, reshaping how projects are planned, executed, and monitored (Lu et al., 2024).

Artificial Intelligence (AI) denotes computational systems capable of performing tasks that typically require human cognitive capabilities, including learning, reasoning, problem-solving, perception, and natural language understanding (Sarker, 2021). It comprises a diverse set of approaches, such as symbolic reasoning, machine learning, neural networks, and evolutionary computation, that enable machines to exhibit adaptive, goal-directed behaviour. According to Rane, Choudhary, and Rane (2024), AI is the creation of intelligent systems that perceive their environment and act rationally to pursue defined objectives. Contemporary AI research emphasises data-driven techniques, particularly machine learning and deep learning, in which algorithms identify patterns in large datasets to generate predictions or decisions with minimal reliance on explicit programming (Taye, 2023).

By leveraging AI, stakeholders can enhance efficiency, reduce costs, and mitigate risks, thereby addressing long-standing industry challenges. AI is reshaping every stage of the construction project lifecycle, from smart design software that optimises architectural plans to predictive maintenance systems that anticipate equipment failures (Baduge et al., 2022). The integration of Artificial Intelligence (AI) within Building Information Modelling (BIM) underscores its transformative potential in the construction domain. AI enhances BIM capabilities by automating design optimisation, facilitating clash detection, and

[1] Corresponding Author
Email address: ajuog@unisa.ac.za

improving resource allocation, thereby streamlining stakeholder collaboration and promoting more efficient and effective project outcomes (Timilsena et al., 2024). This transformation is about adopting new technologies and fostering a culture of innovation, collaboration, and adaptability. The adoption of Artificial Intelligence in the construction and project management sectors offers a strategic response to persistent challenges, including project delays, cost overruns, and resource inefficiencies, while simultaneously facilitating the development of sustainable and resilient infrastructure. (Shamim, 2024).

Across the African continent, awareness of AI applications in construction and project management has increased significantly among policymakers, major contracting firms, and academic institutions; however, practical implementation remains limited and uneven. Continental assessments show that no African country has surpassed an estimated 20% overall AI diffusion, with adoption largely concentrated in regions with comparatively stronger digital infrastructure and cloud readiness, notably parts of Southern and North Africa. In contrast, many countries continue to lag due to persistent deficits in electricity supply, connectivity, data-centre capacity, and specialised technical skills (Mutambara, 2025). Sector-specific literature and national case studies further reveal that awareness and favourable perceptions of AI frequently exceed actual deployment. Although large firms and research-intensive institutions are piloting AI-enabled tools, such as BIM for advanced planning, risk detection, predictive scheduling, and quality control, most small and medium-sized contractors remain at stages of limited awareness, minimal capacity, or early experimentation (Awe et al., 2025).

Despite its benefits, adopting AI in construction and project management faces challenges, including resistance to change, data privacy concerns, and the need for skilled personnel to operate advanced systems (Shoushtari, Daghighi & Ghafourian, 2024). Addressing these barriers is critical to unlocking the full potential of AI and fostering a culture of innovation in the industry. This study outlines the foundational principles and key components of designing an AI implementation strategy for construction and project management. Grounding the discussion in scholarly research and industry best practices provides a comprehensive strategic framework for stakeholders seeking to harness AI's transformative power in the construction industry.

2. Literature Review

Historically, construction processes were marked by hierarchical systems and rudimentary project management principles, emphasising craftsmanship and manual labour with minimal reliance on formalised planning or scheduling tools. The introduction of computers in the 1990s, as Eastman (2018) noted, revolutionised project management by enabling the adoption of systems theory. This enabled integrated management of resources, time, and costs. In the 21st century, advanced digital technologies have further transformed construction and project management. According to Lu et al. (2024), these technologies emphasise sustainable practices and lean construction principles that minimise waste and risk while improving overall efficiency.

AI adoption within the construction and project management sector remains comparatively modest relative to industries such as manufacturing, healthcare, education, and transportation. Whereas manufacturing and transportation have achieved significant advancements in automation, predictive analytics, and robotics, the construction sector continues to face challenges stemming from fragmented workflows and limited digital integration (Bang & Olsson, 2022). Similarly, healthcare and education exhibit higher levels of technological maturity, increasingly employing AI for diagnostic support, personalised learning, and administrative efficiency (Faiyazuddin et al., 2025). By contrast, Adebayo et al. (2025) observed that AI deployment in construction is still emerging and is predominantly concentrated in domains such as safety monitoring, schedule optimisation, and design automation.

According to Adebayo et al. (2025), the advancement of artificial intelligence (AI) has generated considerable interest in its potential to transform construction and project management by improving cost estimation, scheduling, risk management, quality control, and safety monitoring. A growing body of literature documents promising AI applications, such as machine learning models for predictive cost and schedule performance, computer vision for site inspection and safety compliance, natural language processing for contract analysis, and digital twins coupled with Building Information Modeling (BIM) for integrated project simulations (Akhmedov, 2023; Korke et al., 2023; Khan et al., 2024). The authors underscore the transformative role of artificial intelligence in improving project efficiency, productivity, accuracy, and decision-making, while simultaneously addressing persistent challenges of cost overruns, schedule delays, ineffective risk management, and resource misallocation. These studies collectively demonstrate AI's capacity to automate repetitive tasks, augment decision-making under uncertainty, and enable near-real-time feedback loops across project lifecycles.

However, Allouzi and Aljaafreh (2024) emphasised that results vary widely across contexts and that adoption is uneven, suggesting that technical feasibility alone does not guarantee successful implementation. Al-sarafi et al. (2022) examined the adoption drivers and barriers, highlighting organisational, technical, and socio-cultural factors that mediate the translation of AI pilots into scaled benefits. Organisational readiness, including executive sponsorship, cross-functional governance, and change management capabilities, is repeatedly identified as a precondition for AI adoption in the construction industry (Fasasi et al., 2024; Khan et al., 2025).

Furthermore, Regona et al. (2022) identified data-related constraints, including fragmented data sources, poor data quality, limited interoperability between BIM and enterprise systems, and limited information technology (IT) infrastructure, as pervasive technical bottlenecks. Shang et al. (2023) highlighted human factors, skills shortages in data science and AI, while Oke et al. (2023) pointed to employee resistance rooted in perceived job threat or low trust in opaque models. Besides, Shakibaei (2024) described regulatory compliance, contractual complexities, and ethical concerns as critical barriers to implementing AI in the construction and project management sector.

A significant strand of the literature focuses on governance, ethics, and risk management for AI in construction. For instance, Shakibaei (2024) called for clear data governance frameworks, model validation and explainability protocols, and mechanisms to mitigate algorithmic bias, especially where models influence safety-critical decisions or contractual outcomes. Asadollahi et al. (2025) highlighted the value of external partnerships with technology vendors, academic institutions, and industry consortia to accelerate capability building and diffuse best practices.

Nevertheless, cost–benefit analysis in the literature is often context-specific and rarely accounts for longer-term organisational change costs, leaving decision-makers seeking scalable project cases with a gap. This has called for interdisciplinary research that integrates technical performance metrics with socio-technical assessments to examine how governance, trust, and legal frameworks shape AI's ultimate effectiveness in construction project ecosystems. Addressing this gap will allow a move beyond isolated proofs of concept toward developing a comprehensive AI implementation strategy that fuses digital infrastructure, skill development, policy support, stakeholder engagement, and industry collaboration, and is technically robust and organisationally sustainable to drive the adoption of AI in construction and project management.

3. Research Methodology

The study employs a systematic literature review methodology, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) in the identification, screening, selection, and synthesis of relevant academic and grey literature to ensure a rigorous and transparent analysis of existing literature. Review research involves applying scientific methods to analyse and synthesise previous studies, thereby generating new knowledge for academic, practical, and policy-making purposes (Kunisch et al., 2023). The primary motivation for reviewing and analysing academic articles is to identify research gaps, explore under-researched areas, and facilitate the development of new theories or ideas (Marzi et al., 2024).

This research study review follows a series of steps to achieve the desired outcome. In the initial phase, a comprehensive keyword search was conducted across leading academic databases: Scopus, Google Scholar, and Web of Science and from other databases for book chapters and conference proceedings using terms like Artificial Intelligence in Construction, Construction Industry, Construction Project Management, Construction Automation, Construction Design, and Predictive Analytics in Construction.

Search keywords were derived from the study's core concepts, with Boolean operators (AND, OR) and wildcards applied to optimise the retrieval of relevant literature. The search strings used were: ("Artificial Intelligence" OR "AI" OR "AI Technologies") AND ("Construction" OR "Construction Project Management" OR "Construction Automation" OR "Predictive Analytics in Construction") AND ("Global South" OR "Africa") AND ("Digital Transformation"). The sample of the search strings used in the database is: ABS-KEY ("Artificial Intelligence "AND (Construction" OR "Construction Project Management" OR "Construction Automation" OR "Predictive Analytics in Construction") Global South AND Africa) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")).

The inclusion and exclusion criteria were defined to maintain a clear focus on the research area. Studies were included if they met the following criteria: they examined the impact of artificial intelligence in construction and project management; were published in peer-reviewed journals, academic conferences, or reputable research reports; and were written in English. Conversely, studies were excluded if they were purely theoretical or conceptual, lacked empirical evidence on the adoption of artificial intelligence in construction and project management, or focused broadly on digital technologies rather than artificial intelligence specifically. The study spans 2018 to 2025 to capture the latest trends and advancements, and specifically addresses aspects of construction and project management. At this stage, 872 peer-reviewed articles and 29 grey literature articles were identified for the study.

A thorough screening process was then carried out, following the defined inclusion and exclusion criteria, to ensure relevance and quality. Duplicate entries and articles unrelated to the construction industry or without AI applications were removed. Following the exclusion of duplicate, irrelevant, and out-of-focus studies, 82 articles and nine grey literature items, consisting of conference proceedings, book chapters, and policy reports, were assessed for eligibility. The deduplication features of the specialised screening tool, Systematic Review Accelerator, were used to identify duplicate records, which were then further examined through side-by-side comparison to confirm their validity as accurate duplicates.

The study progressed to a comprehensive thematic analysis phase to clarify the current status, limitations, and future trends of AI applications in construction and project management. The focus was primarily on key findings and conclusions from the reviewed articles, specific challenges, identified opportunities, and recommendations for policy, practice, and further research. A final set of 54 peer-reviewed articles, six book chapters, and three conference proceedings was selected for thematic analysis.

A PRISMA flow diagram for the study is shown in Figure 1, illustrating the document selection process and thereby enhancing methodological rigour and ensuring transparency in the review.

iterative analytical procedure. Relevant information was first systematically extracted from the selected studies using a predefined coding framework designed to capture conceptual, empirical, and contextual insights related to artificial intelligence, construction automation, construction project management, and predictive analytics in construction. The coded data segments were then analysed thematically to identify patterns, points of convergence, and conceptual linkages, which were subsequently synthesised into higher-order themes representing dominant narratives and recurring constructs within the literature. Through axial coding, the interrelationships among these themes were further examined to elucidate underlying structural connections, dependencies, and potential causal pathways.

The quality appraisal process followed PRISMA guidelines, ensuring methodological transparency, rigorous evaluation of evidence, and reducing potential bias throughout the review process. All eligible studies and reports were assessed using the Critical Appraisal Skills Programme (CASP) Qualitative Checklist, a structured instrument designed to evaluate the methodological rigour and credibility of qualitative research. The appraisal criteria were applied independently by the two authors to strengthen consistency and limit subjectivity, with any divergences resolved through discussion. The outcomes of this appraisal informed decisions

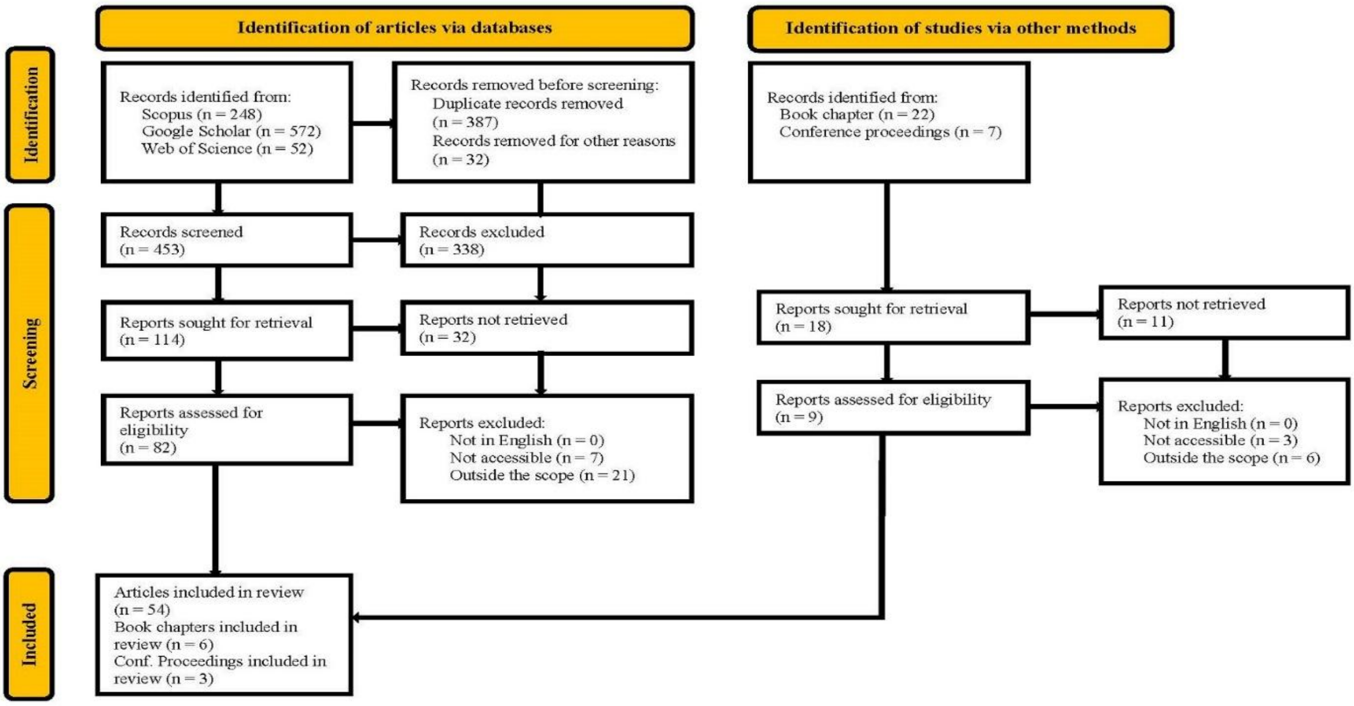

Figure 1: Prisma Flow Diagram for the Study (Source: Authors)

The transition from data extraction to thematic categorisation, and the subsequent development of the implementation strategy, were guided by a rigorous,

regarding the inclusion, exclusion, and weighting of studies within the synthesis, thereby enhancing the reliability, credibility, and overall methodological integrity of the systematic review.

4. Findings

4.1. Application of Artificial Intelligence in Construction and Project Management

The literature indicates that the adoption of AI technologies in construction and project management is accelerating but remains uneven. In contrast, pilot projects and academic studies show substantial gains in scheduling, cost forecasting, safety monitoring, and design optimisation; the full-scale, organisation-wide deployment lags in the leading industries (Ivanova et al., 2023). Recent structured reviews and empirical studies report a surge in research and applied pilots across machine learning, computer vision, robotics, and decision-support systems. However, they repeatedly note that the construction sector is still catching up in turning these pilots into routine practice (Adebayo et al., 2025).

Artificial Intelligence (AI) in construction and project management involves exploiting advanced technologies to improve efficiency, accuracy, and decision-making. According to Akhmedov (2023), AI-driven tools, such as generative design software, enable architects and engineers to rapidly explore numerous design alternatives while optimising key factors, including cost, sustainability, and structural integrity. Baduge et al. (2022) posited that AI algorithms leverage historical data to predict project timelines, identify potential risks, forecast delays, and propose corrective actions. These are made possible through the optimisation of project schedules using generative scheduling, resource allocation, and risk assessment.

Yu and Wang (2022) asserted that adopting AI-powered systems in construction projects enables organisations to identify trends, predict potential issues, and make informed decisions based on accurate, up-to-date information. This assertion is supported by Khan et al. (2024), who confirm the excellent performance of AI systems in analysing real-time data from Internet of Things (IoT) devices, digital twins, cameras, and sensors, making them highly effective in predicting and preventing accidents on construction sites. Technologies such as computer vision and AI-driven drones enhance site safety by providing real-time monitoring and ensuring compliance with project specifications (Khan et al., 2024).

Integrating AI-driven predictive maintenance into construction projects enables machine learning algorithms and advanced data analytics to analyse large-scale sensor data generated by construction equipment, thereby detecting patterns and anomalies that signal potential equipment failures (Putha, 2022). According to Qi and Tao (2018), predictive maintenance is an advanced equipment management strategy that employs AI algorithms to analyse real-time data, predict potential failures, and implement preventive measures. It adopts a proactive approach, unlike traditional maintenance methods that rely on scheduled inspections or reactive repairs.

Furthermore, the adoption of artificial intelligence (AI) models in construction and project management enhances the accuracy of risk assessment and management by enabling the systematic analysis of large and diverse datasets, including weather patterns, financial trends, and stakeholder behaviours (Pan & Zhang, 2021). Construction projects are inherently complex and multifaceted, demanding effective coordination and streamlined material procurement and logistics management. Okoye et al. (2024) argued that the success of construction projects hinges on the efficiency of the construction supply chain, encompassing the acquisition and movement of materials throughout the project lifecycle. The integration of AI into project management platforms enhances inventory tracking, demand forecasting, and procurement processes through smart procurement strategies, ensuring the timely delivery of materials and equipment (Culot et al., 2024). Regona et al. (2022) observed that the adoption of AI in construction and project management is leading to a more cost-effective, efficient, productive, proactive, safe and sustainable construction industry.

Table 1 (See Appendix 1) presents additional findings on the application of artificial intelligence in construction and project management, specifically in progress monitoring, BIM integration, predictive analytics, robotics, and safety, detailing the contextual settings, AI techniques employed, associated project functions, and key outcomes.

4.2. Impact on Efficiency, Cost, and Time Management

4.2.1. Efficiency

AI-driven digital transformation substantially raises operational efficiency by automating routine tasks, improving information flow across lifecycle stages, and enabling data-driven decision-making. Rinchen, Banihashemi and Alkilani (2024) contended that integrating BIM, IoT and cloud platforms with AI enables real-time clash detection, automated progress-tracking from site sensors and images, and smarter logistics planning, leading to reduced rework, improved worker utilisation, and increased productive output per labour hour. Measurable gains in productivity are observed when artificial intelligence is applied to coordinate design–construction handovers and to automate repetitive scheduling and quality control processes (Adebayo et al., 2025).

Similarly, AI systems utilise condition-based monitoring and predictive analytics techniques to analyse sensor data, enabling proactive maintenance, minimising equipment downtime, and enhancing the efficiency of construction projects (Singh et al., 2023; Shoushtari et al., 2024).

Besides, sustainability and risk management are identified as two domains in which AI's contributions are increasingly documented. AI supports life-cycle carbon estimation by linking design data to material-impact databases, optimises sequencing to reduce waste and transport emissions, and enhances risk quantification across the project lifecycle, helping project managers to prioritise mitigation actions with probabilistic outputs rather than binary judgements (Tian et al., 2025). Also, coupling AI with sustainability metrics creates value for both compliance and operational cost savings, particularly when data fidelity and governance are adequate (Demeke, 2025). By digitising data capture and transforming documents into structured signals, AI tools such as natural language processing and reinforcement learning reduce rework cycles and shorten decision loops from days to hours, a key driver of construction projects' execution efficiency.

4.2.2. Cost

Artificial Intelligence is already reshaping core project-management activities. On cost, AI has a dual effect: it lowers variable and lifecycle costs while raising certain upfront and transition costs. Advanced machine learning models and hybrid deep-learning approaches produce more accurate cost and duration estimates, improving bid accuracy and reducing contingency loading due to uncertainty (Cheng, Vu & Gosal, 2025). AI systems leverage historical project data and external variables to predict risks such as cost overruns, delays, and quality issues (Korke et al., 2023). They improve schedule and cost forecasting by learning from historical project data to flag risks and potential overruns earlier than conventional methods; computer vision systems applied to site imagery automate safety compliance checks and progress quantification; and optimisation algorithms assist resource levelling and logistics for complex supply chains (Nenni et al., 2025).

Datta et al. (2024) observed that predictive maintenance and waste-optimisation models shrink material and downtime costs over a project's life. These targeted applications deliver measurable benefits by reducing rework, fewer safety incidents, tighter schedule control, and improved tender accuracy when integrated with existing workflows and Building Information Modelling (BIM) data. The benefit of adopting the technology is a reduction in the total project cost. Shamim et al. (2025) further argued that integrating AI into project management enhances upfront cost estimation by reducing bias and error, while also enabling more timely mid-course corrections. Together, these effects help mitigate cost overruns that typically arise from the late discovery of project issues.

However, the literature consistently flags significant initial investments (software, sensors, data management), training, and integration costs. It warns that without careful change management, these can offset short-term savings (Khan et al., 2024). Cost-benefit outcomes therefore depend heavily on organisational readiness, data maturity, and scale of deployment.

4.2.3. Time Management

Regarding time management and schedule performance, AI enables earlier and more reliable detection of delay risks and can generate optimised schedules from historical BIM data (Alsulamy, 2025). According to Al-Sinan et al. (2024), machine-learning predictors, such as XGBoost, CatBoost, and deep-learning hybrids, outperformed traditional heuristics in forecasting delays and in prioritising interventions, thereby reducing time to recovery and minimising cascading schedule impacts in construction projects. The authors also maintained that automated schedule generation and continual resequencing reduce manual planning and shorten decision cycles, resulting in faster project delivery across many tested projects. Although these gains are contingent on the availability of clean historical data and integrated workflows that let AI outputs be actioned quickly on site.

Ivanova et al. (2023) stated that AI in infrastructure construction provides safety monitoring, such as personal protective equipment compliance, worker and equipment tracking, and process management, as the most mature application clusters, resulting in fewer stoppages and smoother workflows, which ultimately lead to optimal time usage in projects' execution and timely delivery of projects.

4.3. Challenges of Artificial Intelligence Implementation in the Construction Industry

Incorporating artificial intelligence (AI) into the construction and project management sector holds significant promise for enhancing efficiency, accuracy, and decision-making. Despite this potential, its widespread adoption faces several challenges. These challenges can be broadly classified into five categories: technological, organisational, financial, environmental, and regulatory and ethical challenges.

4.3.1. Technological Challenges

Data issues, including fragmentation, poor quality, and interoperability, repeatedly constrain AI in construction. Construction data comes from heterogeneous sources, such as BIM, sensors, drones, schedule logs, and procurement systems, and is often incomplete, noisy, or stored in proprietary formats, which prevents ready reuse for machine learning (Asadollahi et al., 2025).

According to Regona et al. (2022) and Obiuto et al.

(2024), construction projects often lack standardised data collection processes, leading to inconsistent, incomplete, or siloed data that limit the effectiveness of AI functionalities. The lack of standardised data formats and protocols in the construction sector further complicates AI implementation, as AI systems rely heavily on large volumes of accurate, structured data (Pan & Zhang, 2021). Du et al. (2024) contended that efforts to link BIM semantics to AI-ready feature sets remain immature, as many promising algorithms fail at the pre-processing stage or produce unreliable outputs when fed with inconsistent data. These data-readiness and transformation problems are considered the most-cited technical barriers to deployment.

Besides, the technical limitations of AI models also pose significant risks in construction, as reliance on restricted or biased datasets often yields unreliable and non-generalisable predictions. Such inaccuracies compromise safety-critical decisions and contract documentation in construction (Sinha & Lee, 2024). Furthermore, black-box behaviour, limited explainability, and domain drift, arising from model degradation as site conditions and materials evolve, erode trust among engineers and clients, thereby constraining adoption in high-stakes construction tasks (Ghimire, Kim & Acharya, 2024).

4.3.2. Organisational Challenges

Manpower capability gap, resistance to change, and leadership commitment have been identified as major human and organisational limitations for adopting AI in the construction and project management sector. Obi, Osuizugbo and Awuzie (2025) posited that construction’s traditional workforce and management structures are less familiar with data science, AI lifecycle management, or digital-first work processes. Therefore, the construction industry faces a shortage of professionals skilled in AI and data science, creating a bottleneck for AI implementation (Shang et al., 2023).

Also, resistance to change, low on-site digital literacy, and weak top-down sponsorship reduce the likelihood that construction experiments will become business-as-usual. Many construction professionals hesitate to adopt new technologies due to a lack of familiarity with AI technology or fear of job displacement (Oke et al., 2023). Fasasi et al. (2024) noted that the industry's conservativeness and high fragmentation, characterised by numerous small players and subcontractors, complicate collaboration on AI initiatives. Besides, the concerns about the transparency of AI decision-making processes further erode trust and acceptance among stakeholders (Pan & Zhang, 2021). Singh et al. (2023) assert that without targeted training, clear change management, and executive commitment, AI pilots tend to wither despite technical promise.

4.3.3. Financial Challenges

The high cost and infrastructure burden are also identified as significant challenges to the adoption of AI systems in the construction and project management sectors. The initial capital outlay for sensors, edge devices, cloud services, and integration with legacy enterprise systems is substantial, especially for SME contractors with thin margins. Oke et al. (2023) highlighted the financial and economic hurdles the construction industry faces, particularly the high costs associated with developing and deploying AI solutions, and Korke et al. (2023) argued that implementing AI requires substantial initial investments in software, hardware, and skilled personnel. These upfront costs can be prohibitive, particularly for smaller construction firms.

Additionally, the ongoing costs of model retraining, data storage, cybersecurity, and the uncertainty around short-term return on investment (ROI) make investments risky. Shang et al. (2023) identified cost and unclear economic benefits as primary inhibitors of uptake. Consequently, many organisations either pilot isolated proofs of concept that never scale or delay investment until clear vendor solutions emerge.

4.3.4. Environmental Challenges

The literature presents environmental factors as significant challenges for AI adoption in the construction industry. AI models struggle to handle the unstructured, unpredictable nature of construction sites, while high computational demands often limit their capacity for real-time decision-making (Khan et al., 2025). According to Yang et al. (2024), the operational realities of construction sites, such as temporary setups, dynamic layouts, varied weather conditions, and unstructured human activities, make implementing real-world automation technologies like robotics, autonomous vehicles, and continuous vision monitoring far more difficult than laboratory results suggest.

Unlike controlled environments such as factories and mines, urban construction sites are far more complex. Najafzadeh and Yeganeh (2025) contend that AI deployments in construction frequently require extensive customisation, safety interlocks, and hybrid human–machine workflows, which drive up costs and complexity. Consequently, many of AI's most promising applications remain confined to pilot or demonstration projects rather than achieving full-scale commercial adoption.

4.3.5. Regulatory and Ethical Challenges

Legal, ethical, and cybersecurity issues have been further classified as limitations restricting the use of AI applications in construction environments. Singh et al. (2023) argued that construction collects personal data, such as workers' images, locations, and health metrics, as well as commercial data, such as contracts and bids, raising privacy, compliance, liability, and intellectual property concerns. Cyber-attacks on connected construction assets and poisoned training data can produce safety hazards or commercial losses, just as regulatory ambiguity about AI accountability in many jurisdictions can exacerbate procurement and insurance frictions (Pärn & de Soto, 2020).

Regulatory and ethical barriers, such as data privacy concerns, algorithmic bias, and accountability for AI-driven decisions, have been flagged as challenges to AI adoption in the CPM sector (Re Cecconi, Khodabakhshian & Rampini, 2025). Similarly, Shakibaei (2024) underscored the need for AI systems to adhere to regulations that remain inadequately defined in the construction sector. These governance and trust issues, therefore, slow the mainstreaming of AI.

Therefore, Korke et al. (2023), Obiuto et al. (2024), Oke et al. (2023), and Shakibaei (2024) underscore the importance of developing a comprehensive artificial intelligence implementation strategy specifically tailored to the construction industry, emphasising that such a strategy is essential for unlocking the full potential benefits that artificial intelligence offers to the construction and project management sectors. Table 2 summarises AI-related challenges and their impacts in the construction and project management industries.

5. Discussion

5.1. Synthesis of Findings

The literature indicates a growing trend in the adoption of AI tools across the construction and project management sectors, reflecting industry-wide recognition of AI's transformative potential. Tools such as predictive analytics for risk management, automated scheduling systems, and AI-driven design optimisation are increasingly being integrated into workflows. This adoption signals a shift toward data-driven decision-making and automation, which aligns with global trends toward digital transformation in the construction sector. However, the extent of adoption varies significantly across organisations, often influenced by factors such as organisational readiness, technological infrastructure, and managerial attitudes toward innovation.

In terms of impact on efficiency, cost, and time management, the results suggest that AI has delivered notable improvements in project delivery. Findings reported enhanced forecasting accuracy, reduced project delays through real-time monitoring, and cost optimisation achieved by minimising material waste and resource misallocation (Nenni et al., 2025). These findings underscore AI’s potential to address traditional inefficiencies in construction projects, particularly in complex and large-scale developments where time and budget overruns are common. Moreover, AI’s ability to facilitate predictive maintenance and optimise resource allocation contributes to better risk management and improved overall project performance.

Despite these benefits, the findings highlight persistent challenges and limitations in AI implementation within the construction sector. High initial investment costs, lack of skilled personnel, and resistance to change

Table 2: Summary of Challenges of AI Implementation in CPM (Source: Authors)

Category	Challenges	Impact
Technological (Regona et al., 2022; Obiuto et al., 2024; Du et al., 2024; Asadollahi et al., 2025)	Lack of standardised & quality data; Black-Box Models & Lack of Explainability; Integration with legacy systems; Data & cybersecurity threats	Inaccurate predictions; Unreliable models; Poor decision-making; Reduced trust from Engineers and clients; Risk in safety-critical decisions; Disruptions in workflows; Loss of sensitive project data
Organisational (Oke et al., 2023; Fasasi et al., 2024)	Workforce Resistance; Shortage of professional skills; AI decision-making bias	Slows AI implementation; Social & legal implications; Productivity loss; Underutilisation.
Financial (Korke et al., 2023; Shang et al., 2023)	High initial investment for AI infrastructure; Skilled personnel investments; Limited ROI Evidence	Hesitation among investors and contractors; Slow adoption rates; Limited adoption among SMEs; Delays in scaling AI solutions.
Environmental (Yang et al., 2024; Khan et al., 2025)	Conflicting views on the creation of robots; AI adaptability to unstructured environments;	Models degrade over time, leading to inaccurate outputs, delayed AI adoption, and incorrect AI results and predictions.
Regulatory and Ethical Challenges (Shakibaei, 2024; Re Cecconi, Khodabakhshian & Rampini, 2025)	Cybersecurity & data privacy concerns; Algorithmic bias; Accountability for AI-driven decisions; Legal & Ethical Uncertainty.	Data breaches; Loss of sensitive project data; Reputational damage; Delays in AI adoption, Resistance to data provision, and a Lack of accountability.

emerged as critical barriers (Shoushtari et al., 2024). Furthermore, interoperability issues between AI tools and existing systems, coupled with concerns about data privacy and security, hinder seamless integration (Regona et al., 2022). There is also uncertainty about return on investment (ROI), particularly among small and medium-sized enterprises (SMEs), which limits wider adoption. These challenges suggest that while AI adoption offers substantial benefits, its implementation requires strategic planning, continuous training, and supportive regulatory frameworks to maximise its value in the construction industry.

5.2. Implications for Industry and Practice

The digital transformation of construction and project management through artificial intelligence (AI) carries significant implications for the industry, offering both opportunities and challenges. On the positive side, AI enables data-driven decision-making, real-time monitoring, predictive analytics, and automation of routine tasks, which can lead to improved efficiency, reduced project delays, and optimised resource allocation (Khan et al., 2024). For project managers, AI tools can enhance risk forecasting, schedule optimisation, and cost estimation, while for contractors and clients, they provide greater transparency, accountability, and overall productivity. This transformation aligns with broader industry goals of increasing sustainability, minimising waste, and ensuring projects are delivered on time and within budget.

However, the path to AI integration is not without challenges and risks that shape its practical implications. The cost of adoption, both financial and organisational, remains a barrier, especially for small and medium-sized firms (SMEs) that lack the resources to invest in AI infrastructure and training. Issues of bias and reliability also pose risks, as AI systems trained on incomplete or skewed datasets may produce flawed outputs that can compromise safety-critical decisions or contract documentation (Obiuto et al., 2024). Moreover, the black-box nature of many AI models can erode trust among engineers, project managers, and clients who demand explainability in high-stakes environments. Concerns about data governance, cybersecurity, and compliance further complicate adoption, while workforce resistance to technological disruption may hinder organisational change.

Taken together, these opportunities and risks suggest that while AI can transform construction and project management into a more efficient, predictive, and resilient industry, its implementation must be guided by careful governance, ethical safeguards, and capacity-building strategies. Firms must weigh the tangible benefits of efficiency and competitiveness against the risks of trust erosion, implementation costs, and technological dependency.

A balanced approach that emphasises explainable AI, phased adoption, and workforce upskilling will be critical for ensuring that digital transformation strengthens rather than destabilises the industry, particularly the small and medium construction enterprises (SMEs).

The need for an adaptive, actionable AI implementation strategy for construction and project management, particularly for small and medium-sized enterprises, has become a necessity to exploit the benefits of AI technologies.

5.3. Construction and Project Management Ecosystem

At the heart of the digital transformation of the construction and project management sector through artificial intelligence is the recognition of the inherent complexity and variability of construction projects (Lu et al., 2024). From fluctuating material costs and labour availability to unpredictable weather conditions and regulatory changes, construction project stakeholders face many challenges that demand precision, adaptability, and foresight.

The construction and project management ecosystem is a complex network of stakeholders, processes, and technologies that work together to deliver projects from conception to completion, ensuring that projects are completed on time, within budget, and to the desired quality standards. It includes owners and clients, architects, engineers, contractors, subcontractors, suppliers, regulators, and financial institutions. Each actor contributes to the planning, design, execution, and monitoring of projects, while ensuring compliance with legal, safety, and sustainability standards. The ecosystem is also shaped by broader factors such as policy frameworks, labour markets, technological developments, and environmental considerations, making it both dynamic and multifaceted.

Traditionally, the ecosystem has been characterised by fragmented communication, siloed operations, and manual processes, often leading to inefficiencies, cost overruns, and delays. However, the ongoing wave of digital transformation driven by artificial intelligence (AI) and related technologies offers opportunities to reconfigure these interactions. AI can streamline project planning through predictive analytics, optimise resource allocation, improve safety monitoring, and enable real-time decision-making across stakeholders. This technological infusion is gradually reshaping the ecosystem into a more integrated, data-driven, and collaborative environment, therefore positioning construction and project management for enhanced efficiency, transparency, and sustainability in the digital era. Figure 2 presents the authors' construction and project management ecosystem, taking into

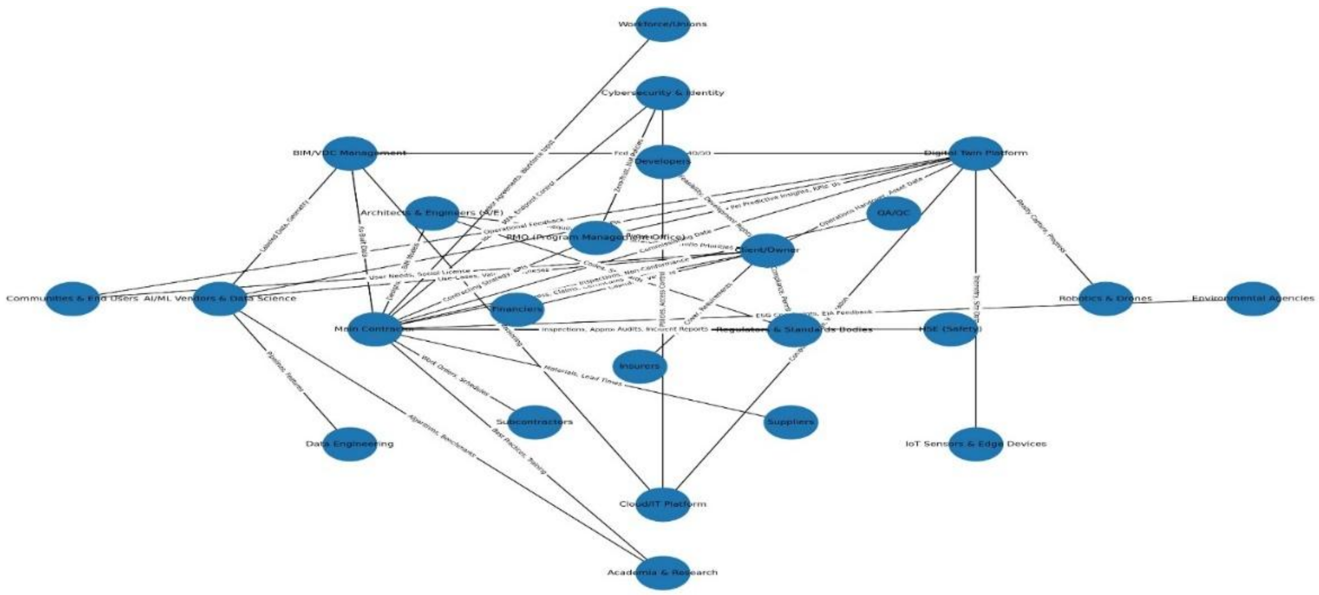

Figure 2: An AI-Integrated Construction and Project Management Ecosystem

consideration the dynamic interactions among the stakeholders.

The ecosystem begins with the governance layer**,** where the Client/Owner, Programme Management Office (PMO), Financiers, Insurers, and Regulators establish the strategic, financial, and compliance framework for projects. These decisions shape feasibility, risk cover, and regulatory approvals, which are then translated into project strategies and key performance indicators (KPIs) by the PMO. From that point, the delivery core takes over, with developers, architects, engineers, and contractors coordinating design, procurement, and construction activities. Subcontractors and suppliers provide specialised services and materials, while Health, Safety and Environment (HSE) and Quality Assurance and Quality Control (QA/QC) ensure that safety, compliance, and quality standards are maintained.

The digital and AI layer amplifies the delivery processes through BIM, IoT sensors, drones, and digital twins that capture real-time data, optimise operations, and support predictive insights. AI/ML models and cloud platforms process this data into actionable intelligence, while cybersecurity safeguards the integrity and trust of digital systems. Finally, the external stakeholders**,** comprising communities, unions, academia, and environmental agencies, provide essential feedback, innovation, and oversight. This creates a continuous flow where governance defines the project direction, delivery executes it, digital technologies optimise and secure it, and external actors regulate and refine it, ensuring sustainable, efficient, and transparent project outcomes. Figure 3 shows a simplified linear ecosystem, with the major layers and their interactions.

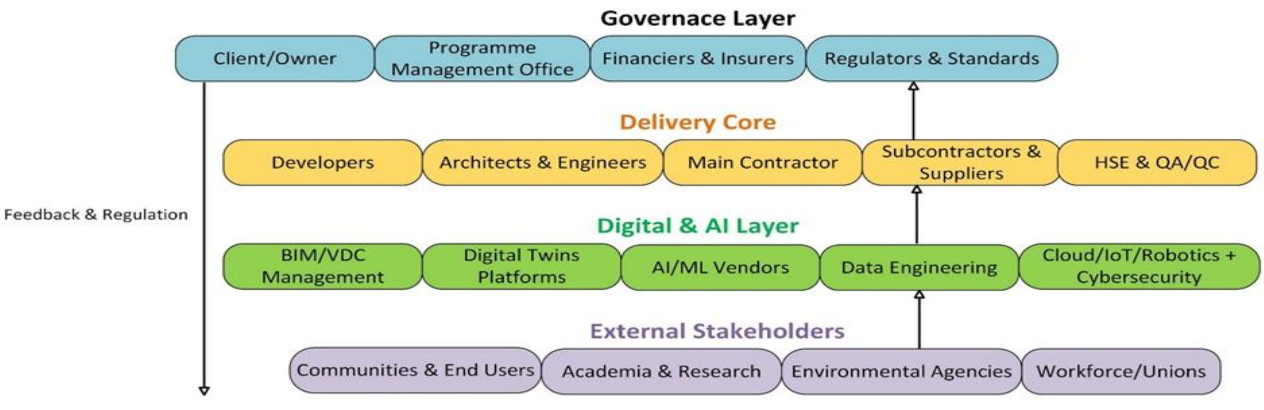

Figure 3: The Simplified Linear Construction and Project Management Ecosystem

5.4. Artificial Intelligence Implementation Strategy for CPM

Although artificial intelligence (AI) holds significant transformative potential for construction and project management, its implementation has been impeded by several challenges, including organisational resistance to change, concerns about data privacy, and a shortage of skilled personnel to manage advanced digital systems. Overcoming these barriers is essential to fully realise the benefits of AI and cultivate a culture of innovation across the industry. To this end, a comprehensive AI implementation strategy is developed that emphasises capacity building, supportive policy frameworks, and enhanced collaboration among stakeholders and industry actors to facilitate effective and sustainable AI adoption in construction and project management. The diagram for the proposed Artificial Intelligence Implementation Strategy for CPM is represented in Figure 4.

champion AI initiatives and ensure that adoption supports broader organisational strategies. Choosing the right AI tools is central to success. Tools such as Building Information Modelling (BIM) for design optimisation, predictive analytics for risk anticipation, and computer vision for site safety monitoring can provide direct value to construction projects.

To reduce risks, organisations should implement a pilot programme**,** starting small with a specific use case such as predictive scheduling using machine learning or drone-based site inspections. Success metrics, such as cost savings, efficiency gains, or error reduction, should be established to evaluate the pilot's impact. Strategic collaboration with reputable vendors experienced in the construction domain ensures the selected solutions are both practical and robust. Supporting this is the need to build infrastructure and skills**,** ensuring data readiness through clean, structured

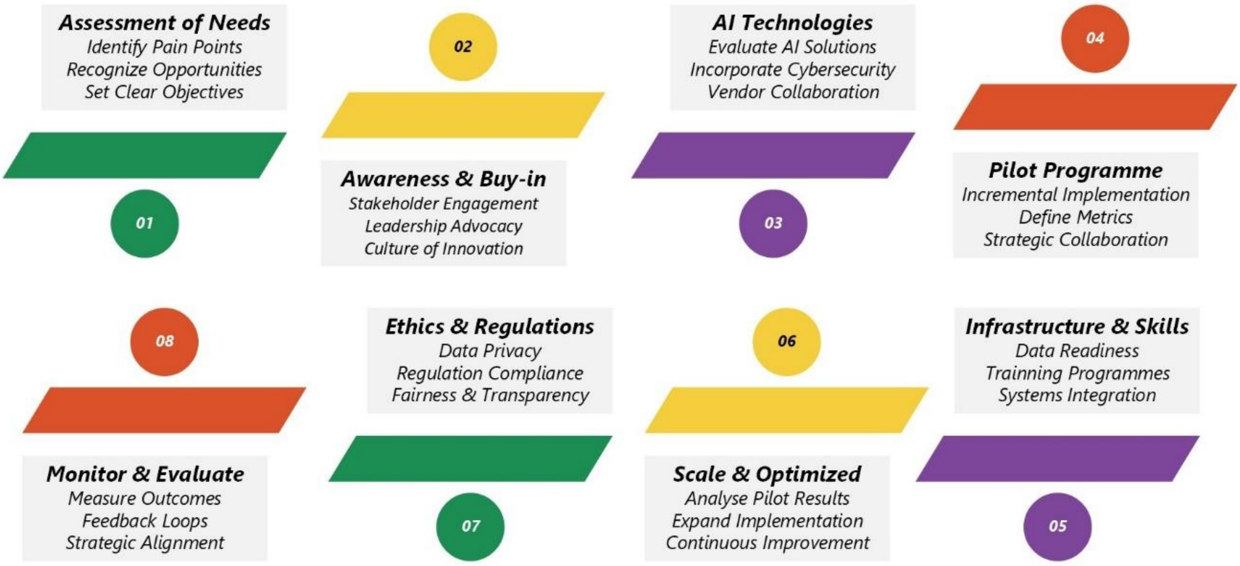

Figure 4: Proposed Artificial Intelligence Implementation Strategy for CPM

The implementation strategy begins with a clear assessment of an organisation's needs and opportunities**.** Organisations must identify critical pain points such as delays in project scheduling, inefficient resource allocation, safety risks, and challenges in quality control or predictive maintenance. Once these are evaluated, clear objectives should be set, for example, minimising project delays, improving safety compliance, and optimising material usage, ensuring that AI adoption is aligned with business priorities and measurable goals.

The next step is to build awareness and buy-in across the organisation. Engaging stakeholders, such as project managers, engineers, contractors, and site workers, is essential to fostering understanding and addressing concerns about AI's role. Equally important is leadership advocacy from senior management to

datasets, providing training programmes to upskill employees, and integrating AI tools with existing project management systems to ensure seamless workflows.

Once the pilot demonstrates value, organisations can scale and optimise AI applications. Insights from early adoption should inform refinements, after which implementation can be expanded across multiple projects. Continuous monitoring and improvement, including updating algorithms and adapting to new project requirements, will maintain long-term effectiveness. In parallel with scaling, organisations must also address ethical and regulatory considerations**,** particularly by ensuring data privacy, regulatory compliance, and fairness in AI decision-making. Maintaining transparency in how AI systems make recommendations builds trust with stakeholders.

Finally, measuring return on investment (ROI) and long-term impact is vital for sustaining AI implementation. This includes evaluating outcomes such as reduced costs, improved project timelines, enhanced safety, and higher-quality outputs. A feedback loop with architects, engineers, and project managers helps refine AI tools. At the same time, continuous alignment with the organisation's strategic vision ensures AI delivers sustainable benefits to construction and project management practices.

5.5. Development of the Proposed Implementation Strategy Based on Literature Findings

The developed implementation strategy is directly derived from the study's empirical findings and is structured to respond systematically to the identified thematic insights. The theme on the application of Artificial Intelligence in construction and project management informed the assessment of needs and AI technologies components by identifying priority use cases, functional areas, and suitable AI tools aligned with industry practices. Findings on the impact of AI on efficiency, cost, and time management underpin the pilot programmes, and scale and optimisation components, providing evidence-based justification for incremental adoption, performance benchmarking, and the expansion of successful AI applications. These impact-related findings also guided the monitor and evaluate component, ensuring that measurable productivity, cost, and scheduling indicators are embedded in implementation and review processes.

The theme on the challenges of AI implementation, including technological, organisational, financial, environmental, and ethical constraints, informed the remaining strategy components. Specifically, organisational and cultural barriers shaped awareness and buy-in, while technological and skills gaps guided infrastructure and skills development. The financial challenge reinforced the need for phased pilot programmes before large-scale deployment. Furthermore, ethical, regulatory, and governance concerns directly informed the ethics and regulations component, ensuring responsible and compliant AI adoption. Collectively, these thematic linkages ensure that the implementation strategy is empirically grounded, context-sensitive, and aligned with both the opportunities and constraints identified in the study.

6. Conclusion

This study synthesises recent AI in construction and project management (CPM) literature, conceptualises an AI-integrated CPM ecosystem, and develops a strategic framework for the implementation of artificial intelligence (AI) in the construction and project management sector, addressing the industry's increasing demand for digital transformation and enhanced operational efficiency. The study's findings highlight AI's substantial potential to improve project outcomes through more informed decision-making, accurate forecasting, optimised resource allocation, and effective risk management. Moreover, the study underscores that realising the full benefits of AI extends beyond mere technological adoption, necessitating a comprehensive strategy that encompasses organisational leadership, capacity building, stakeholder engagement, and supportive policy measures.

From an industry perspective, the proposed AI implementation strategy provides a roadmap for both practitioners and policymakers to embed AI in ways that are context-sensitive, scalable, and sustainable. By situating AI within broader organisational and regulatory ecosystems, the framework encourages innovation while mitigating risks related to trust, cost, and operational disruption. In doing so, it advances the digital maturity of the construction and project management domain, offering a pathway toward more resilient, data-driven, and future-ready industry practices.

Finally, the major limitation of this study is the lack of validation of the development strategy. Future research may focus on developing standardised data collection processes that prioritise data privacy and cybersecurity—empirically validating the proposed strategy through case studies and pilot projects to assess its practical applicability across different project scales and contexts. In addition, longitudinal research could examine how the AI implementation strategy evolves, capturing the dynamic interplay among technological advancement, industry adaptation, and governance structures.

References

Adebayo, Y., Udoh, P., Kamudyariwa, X. B. & Osobajo, O. A. (2025). Artificial Intelligence in Construction Project Management: A Structured Literature Review of Its Evolution in Application and Future Trends. *Digital*, 5(3), 26. https://doi.org/10.3390/digital5030026

Akhmedov, A. (2023). Leveraging Artificial Intelligence for Construction Project Scheduling. *Eurasian Journal of Engineering and Technology*, 22, 33–36.

Alateeq, M. M., Rageena, F. P. P., & Ali, M. A. S. (2023). Construction Site Hazards Identification Using Deep Learning and Computer Vision. *Sustainability*, 15(3), 2358. https://doi.org/10.3390/su15032358

Alazawy, S. F. M., Ahmed, M. A., Raheem, S. H., Imran, H., Bernardo, L. F. A. & Pinto, H. A. S. (2025). Explainable Machine Learning to Predict the Construction Cost of a Power Plant Based on Random Forest and Shapley Method. *CivilEng*, 6(2), 21. https://doi.org/10.3390/civileng6020021

Allouzi, M. & Aljaafreh, M. (2024). Applied AI in Neom Construction Projects: The Potential Impact of AI in Enhancing Project Success. *Acta Informatica Malaysia*, 8(1), 32-44. http://doi.org/10.26480/aim.01.2024.32.44

Al-sarafi, A. H. M., Alias, A. H., Shafri, H. Z. M. & Jakarni, F. M. (2022). Factors Affecting BIM Adoption in the Yemeni Construction Industry: A Structural Equation Modelling Approach. *Buildings*, *12*(12), 2066. https://doi.org/10.3390/buildings12122066

Al-Sinan, M. A., Bubshait, A. A., & Aljaroudi, Z. (2024). Generation of construction scheduling through machine learning and BIM: A blueprint. *Buildings*, 14(4), 934. https://doi.org/10.3390/buildings14040934

Alsulamy, S. (2025). Predicting construction delay risks in Saudi Arabian projects: A comparative analysis of CatBoost, XGBoost, and LGBM. *Expert Systems with Applications*, 268, 126268. https://doi.org/10.1016/j.eswa.2024.126268

Asadollahi, H., El Meouche, R., Zheng, Z., Eslahi, M. & Farazdaghi, E. (2025). Bridging building information systems: A parameter-efficient semantic approach to construction data interoperability. *Engineering Applications of Artificial Intelligence*, 155, 110680. https://doi.org/10.1016/j.engappai.2025.110680

Awe, M., Malhi, A., Budka, M., Mavengere, N. & Dave, B. (2025). Towards 4D BIM: A Systematic Literature Review on Challenges, Strategies and Tools in Leveraging AI with BIM. *Buildings*, 15(7), 1072. https://doi.org/10.3390/buildings15071072

Baduge, S. K., Thilakarathna, S., Perera, J. S., Arashpour, M., Sharafi, P., Teodosio, B., Shringi, A., & Mendis, P. (2022). Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications. *Automation in Construction*, 141, 104440.

Bang, S. & Olsson, N. (2022). Artificial Intelligence in Construction Projects: A Systematic Scoping Review. *Journal of Engineering, Project, and Production Management*, 12(3), 224-238. https://doi.org/10.32738/JEPPM-2022-0021

Cheng, M. Y., Vu, Q. T. & Gosal, F. E. (2025). Hybrid deep learning model for accurate cost and schedule estimation in construction projects using sequential and non-sequential data. *Automation in construction*, 170, 105904. https://doi.org/10.1016/j.autcon.2024.105904

Culot, G., Podrecca, M. & Nassimbeni, G. (2024). Artificial Intelligence in Supply Chain Management: A Systematic Literature Review of Empirical Studies and Research Directions. *Computers in Industry*, 162, 104132. https://doi.org/10.1016/j.compind.2024.104132

Datta, S. D., Islam, M., Sobuz, M. H. R., Ahmed, S. & Kar, M. (2024). Artificial intelligence and machine learning applications in the project lifecycle of the construction industry: A comprehensive review. *Heliyon*, 10(5). https://doi.org/10.1016/j.heliyon.2024.e26888

Demeke, C. S. 2025. Exploring the Integration of Artificial Intelligence and Sustainability Practices in Project Management: Challenges and Opportunities. *International Journal of Computer Applications*, 186(73), 34-42. https://doi.org/10.5120/ijca2025924600

Du, S., Hou, L., Zhang, G., Tan, Y., & Mao, P. (2024). BIM and IFC Data Readiness for AI Integration in the Construction Industry: A Review Approach. *Buildings*, 14(10), 3305. https://doi.org/10.3390/buildings14103305

Eastman, C. M. (2018). Building Product Models: Computer Environments, Supporting Design and Construction. Boca Raton, CRC press.

Ekanayake, B., Wong, J. K., Fini, A. A. F. & Smith, P. (2021). Computer Vision-Based Interior Construction Progress Monitoring: A Literature Review and Future Research Directions. *Automation in Construction*, 127, 103705. https://doi.org/10.1016/j.autcon.2021.103705

Faiyazuddin, M., Rahman, S. J. Q., Anand, G., Siddiqui, R. K., Mehta, R., Khatib, M. N., Gaidhane, S., Zahiruddin, Q. S., Hussain, A., & Sah, R. (2025). The Impact of Artificial Intelligence on Healthcare: A Comprehensive Review of Advancements in Diagnostics, Treatment, and Operational Efficiency. *Health Science Reports*, 8(1), e70312. https://doi.org/10.1002/hsr2.70312

Fasasi, M., Aminu, M. B. & Ogunmilua, O. K. (2024). Assessing Drivers and Barriers to the Adoption of Smart Technologies in the Construction Industry: A Quantitative Study. *Journal of Materials Engineering, Structures and Computation*, 3(2). https://doi.org/10.5281/zenodo.11400958

Ghimire, P., Kim, K., & Acharya, M. (2024). Opportunities and Challenges of Generative AI in Construction Industry: Focusing on Adoption of Text-Based Models. *Buildings*, 14(1), 220. https://doi.org/10.3390/buildings14010220

Ivanova, S., Kuznetsov, A., Zverev, R. & Rada, A. (2023). Artificial intelligence methods for the construction and management of buildings. *Sensors*, 23(21), 8740. https://doi.org/10.3390/s23218740

Khan, A. A., Bello, A. O., Arqam, M., & Ullah, F. (2024). Integrating Building Information Modelling and Artificial Intelligence in Construction Projects: A Review of Challenges and Mitigation Strategies. *Technologies*, 12(10), 185.

Khan, A., Halimi, S.M.M., Saad, S., Rasheed, K. & Ammad, S. (2025). Robotics in Construction: Transforming the Built Environment. In Saad, S., Rasheed, K. and Ammad, S. Applications of Digital Twins and Robotics in the Construction Sector, 1st Edition, pp. 23-48. Boca Raton, CRC Press. https://doi.org/10.1201/9781003518747

Korke, P., Gobinath, R., Shewale, M. & Khartode, B. (2023). Role of Artificial Intelligence in Construction Project Management. In E3S Web of Conferences (Vol. 405, 04012). *EDP Sciences*. https://doi.org/10.1051/e3sconf /202340504012

Kunisch, S., Denyer, D., Bartunek, J. M., Menz, M. & Cardinal, L. B. (2023). Review Research as Scientific *Inquiry. Organisational Research Methods,* 26(1), 3-45. https://doi.org/10.1177/10944281221127292.

Liu, L., Guo, Z., Liu, Z., Zhang, Y., Cai, R., Hu, X., Yang, R., & Wang, G. (2024). Multi-Task Intelligent Monitoring of Construction Safety Based on Computer Vision. *Buildings, 14*(8), 2429. https://doi.org/10.3390/buildings14082429

Lu, W., Lou, J., Ababio, B. K., Zhong, R. Y., Bao, Z., Li, X. & Xue, F. (2024). Digital technologies for construction sustainability: Status quo, challenges, and future prospects. *npj Materials Sustainability*, 2(1), 10.

Marzi, G., Balzano, M., Caputo, A. & Pellegrini, M. M. (2024). Guidelines for Bibliometric-Systematic Literature Reviews: 10 Steps to Combine Analysis, Synthesis and Theory Development. *International Journal of Management Reviews* 27, 81-103. https://doi.org/10.1111/ijmr.12381.

Musarat, M. A., Alaloul, W. S., Rostam, N. A. Q., & Khan, A. M. (2024). Substitution of workforce with robotics in the construction industry: A wise or witless approach. *Journal of Open Innovation: Technology, Market, and Complexity*, 10(4), 100420. https://doi.org/10.1016/j.joitmc.2024.100420

Mutambara, A. G. (2025). Artificial Intelligence: A Driver of Inclusive Development and Shared Prosperity for the Global South. Boca Raton, CRC Press.

Najafzadeh, M. & Yeganeh, A. (2025). AI-Driven Digital Twins in Industrialised Offsite Construction: A Systematic Review. *Buildings*, 15(17), 2997. https://doi.org/10.3390/buildings15172997

Nenni, M. E., De Felice, F., De Luca, C. & Forcina, A. (2025). How artificial intelligence will transform project management in the age of digitisation: a systematic literature review. *Management Review Quarterly,* 75, 1669–1716. https://doi.org/10.1007/s11301-024-00418-z

Obi, L., Osuizugbo, I. C. & Awuzie, B. O. (2025). Closing the Artificial Intelligence Skills Gap in Construction: Competency Insights from a Systematic Review. *Results in Engineering*, 27, 106406. https://doi.org/10.1016/j.rineng.2025.106406

Obiuto, N. C., Adebayo, R. A., Olajiga, O. K. & Festus-Ikhuoria, I. C. (2024). Integrating Artificial Intelligence in Construction Management: Improving Project Efficiency and Cost-Effectiveness. *Int. J. Adv. Multidisc. Res. Stud*, 4(2), 639-647.

Oke, A. E., Aliu, J. & Onajite, S. A. (2023). Barriers to the adoption of digital technologies for sustainable construction in a developing economy. *Architectural Engineering and Design Management*, 20(3), 431–447. https://doi.org/10.1080/17452007.2023.2187754

Okoye, C. C., Ofodile, O. C., Tula, S. T., Nifise, A. O. A., Falaiye, T., Ejairu, E., & Addy, W. A. (2024). Risk management in international supply chains: A review with USA and African Cases. *Magna Scientia Advanced Research and Reviews*, 10(1), 256-264. https://doi.org/10.30574/msarr.2024.10.1.0024

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., & Chou, R. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ, 372. https://doi.org/10.1136/bmj.n71

Pan, Y. & Zhang, L. (2021). Roles of Artificial Intelligence in Construction Engineering and Management: A Critical Review and Future Trends. *Automation in Construction*, 122, 103517. https://doi.org/10.1016/j.autcon.2020.103517.

Pärn, E. A. & de Soto, B. G. (2020). Cyber threats and actors confronting the Construction 4.0. In: Sawhney, A., Riley, M and Irizarry, J. Construction 4.0, 1st Edition, London, Routledge, 441-459. https://doi.org/10.1201/9780429398100

Putha, S. (2022). AI-Driven Predictive Maintenance for Smart Manufacturing: Enhancing Equipment Reliability and Reducing Downtime. *Journal of Deep Learning in Genomic Data Analysis*, 2(1), 160-203.

Qi, Q. & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access*, 6, 3585-3593. https://doi.org/10.1109/ACCESS.2018.2793265

Rane, N., Choudhary, S. and Rane, J. (2024). Artificial Intelligence for Enhancing Resilience. *Journal of Applied Artificial Intelligence,* 5(2), 1-33. https://doi.org/10.48185/jaai.v5i2.1053

Ranjan, R., Jagannathan, M., Chandran, P. R. & Doloi, H. (2025). Addressing Documentation Issues in Construction Claims Using Natural Language Processing. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 17(4), 04525047. https://doi.org/10.1061/JLADAH.LADR-1348

Re Cecconi, F., Khodabakhshian, A. & Rampini, L. (2025). Industry 5.0 in Construction: Towards a More Human-Centric and Ethical AI. In Building Tomorrow: Unleashing the Potential of Artificial Intelligence in Construction (101-122). Cham, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-031-77197-2_6

Regona, M., Yigitcanlar, T., Xia, B. & Li, R. Y. M. (2022). Opportunities and adoption challenges of AI in the construction industry: A PRISMA review. *Journal of open innovation: technology, market, and complexity*, 8(1), 45. https://doi.org/10.3390/joitmc8010045

Rinchen, S., Banihashemi, S. & Alkilani, S. (2024). Driving digital transformation in construction: Strategic insights into building information modelling adoption in developing countries. *Project Leadership and Society*, 5, 100138. https://doi.org/10.1016/j.plas.2024.100138

Sarker, I. H. (2021). Machine Learning: Algorithms, Real-World Applications and Research Directions. *SN Computer Science,* 2(160). https://doi.org/10.1007/s42979-021-00592-x

Shakibaei, R. (2024). Artificial Intelligence in the Effective Execution Process of Construction Projects in the Future. *Journal of Economics, Management and Trade*, 30(6), 75-87. https://doi.org/10.9734/jemt/2024/v30i61215

Shamim, M. M. I. (2024). Artificial Intelligence in Project Management: Enhancing Efficiency and Decision-Making. *International Journal of Management Information Systems and Data Science*, 1(1), 1-6. https://doi.org/10.62304/ijmisds.v1i1.107

Shamim, M. M. I., Hamid, A. B. B. A., Nyamasvisva, T. E. & Rafi, N. S. B. (2025). Advancement of Artificial Intelligence in Cost Estimation for Project Management Success: A Systematic Review of Machine Learning, Deep Learning, Regression, and Hybrid Models. *Modelling*, *6*(2), 35. https://doi.org/10.3390/modelling6020035

Shang, G., Low, S. P. & Lim, X. Y. V. (2023). Prospects, drivers of and barriers to artificial intelligence adoption in project management. *Built Environment Project and Asset Management*, 13(5), 629-645. https://doi.org/10.1108/BEPAM-12-2022-0195

Shoushtari, F., Daghighi, A. & Ghafourian, E. (2024). Application of Artificial Intelligence in Project Management. *International journal of industrial engineering and operational research*, 6(2), 49-63.

Singh, A. K., Pal, A., Kumar, P., Lin, J. J., & Hsieh, S. H. (2023). Prospects of integrating BIM and NLP for automatic construction schedule management. In ISARC. *Proceedings of the International Symposium on Automation and Robotics in Construction*, 40, 238-245.

Singh, A., Dwivedi, A., Agrawal, D. & Singh, D. (2023). Identifying issues in adoption of AI practices in construction supply chains: towards managing sustainability. *Operations Management Research*, 16(4), 1667-1683. https://doi.org/10.1007/s12063-022-00344-x

Sinha, S. & Lee, Y. M. (2024). Challenges with developing and deploying AI models and applications in industrial systems. *Discover Artificial Intelligence*, 4(1), 55. https://doi.org/10.1007/s44163-024-00151-2

Taye, M. M. (2023). Understanding of Machine Learning with Deep Learning: Architectures, Workflow, Applications and Future Directions. *Computers,* 12(5), 91. https://doi.org/10.3390/computers12050091

Tian, K., Zhu, Z., Mbachu, J., Ghanbaripour, A. & Moorhead, M. (2025). Artificial intelligence in risk management within the realm of construction projects: A bibliometric analysis and systematic literature review. *Journal of Innovation & Knowledge*, 10(3), 100711. https://doi.org/10.1016/j.jik.2025.100711

Timilsena, P. R., Tummalapudi, M., Hyatt, B., Bangaru, S., & Ogunseiju, O. (2024). Applications of Artificial Intelligence (AI) in Construction Project Management: A Systematic Literature Review. In The 10th International Conference on Construction Engineering and Project Management, Korea Institute of Construction Engineering and Management, Sapporo. https://dx.doi.org/10.6106/ICCEPM.2024.0293

Valdebenito, R. and Forcael, E. (2025). Integrating Artificial Intelligence and BIM in Construction: Systematic Review and Quantitative Comparative Analysis. *Applied Sciences*, 15(23), 12470. https://doi.org/10.3390/app152312470

Yang, Z., Tang, C., Zhang, T., Zhang, Z. & Doan, D. T. (2024). Digital twins in construction: Architecture, applications, trends and challenges. *Buildings*, 14(9), p.2616. https://doi.org/10.3390/buildings14092616

Yu, T. & Wang, X. (2022). Real-Time Data Analytics in Internet of Things Systems. In: Handbook of Real-Time Computing (541-568). Singapore: Springer Nature

.

Appendix 1

Table 1: The application of artificial intelligence in construction and project management

Author/Year/ Ref	Context (Setting)	AI Technique	CPM Function	Main Outcomes
Ekanayake et al. (2021). Computer vision for interior progress monitoring.	On-site interior finishing works (case studies).	Convolutional neural networks (CNNs), image processing, and photogrammetry	Progress monitoring, productivity measurement, and quality assurance.	Automated image-based progress monitoring reduced manual reporting time, improved the accuracy of per cent-complete estimates, and enabled near real-time productivity tracking.
Yu & Wang (2022). Real-Time Data Analytics.	Case studies & simulations in feasibility/scheduling contexts.	Predictive ML (time-series, ensemble models), scenario simulation.	Feasibility analysis, schedule risk forecasting, and decision support.	Demonstrated improved uncertainty quantification in feasibility studies and better schedule risk prediction.
Alateeq et al. (2023) Construction Site Hazards Identification.	Construction site image datasets / real projects.	Deep learning (CNNs, image classification/ object detection).	Site safety monitoring; hazard identification; automated alerts.	Validated deep-learning pipelines for multi-class hazard detection; highlighted data scarcity and annotation challenges.
Musarat et al. (2024). Robotics & workforce substitution in construction.	Empirical studies on robotic deployments on-site.	AI-driven robotics for control/ planning, autonomous navigation.	Automation of repetitive tasks, labour substitution, and productivity.	Robotics increase productivity for specific tasks and reduces exposure to hazardous work; adoption is constrained by cost, task variability, and integration with human crews.
Liu et al. (2024). Computer vision for construction safety monitoring.	Active construction sites (video surveillance datasets).	Deep learning (YOLO family adaptations), multi-task CNNs.	Safety monitoring, Personal Protective Equipment (PPE) detection.	Multi-task models detected PPE non-compliance and unsafe behaviours with high precision, supporting proactive safety interventions and lowering incident risk.
Valdebenito et al. (2025). Integrating AI and BIM — review & synthesis.	Recent literature synthesis (2022–2025).	ML, knowledge graphs, and semantic rule engines integrated with BIM.	Planning, clash detection, lifecycle data analytics.	Shows convergent trend: AI services plugged into BIM workflows enable predictive asset management, automated code checking, and improved handover.
Alazawy et al. (2025). Machine Learning to Predict the Construction Cost.	Power-plant construction case studies.	Explainable ensemble ML (feature-importance, SHAP-style explanations).	Early cost prediction; model interpretability for stakeholder buy-in.	Demonstrated improved prediction accuracy from ensembles and provided feature-level explanations to increase trust and practical uptake in project planning.
Ranjan (2025). Addressing Construction Claims Using Natural Language Processing.	Claims and contract correspondence (construction projects).	NLP (Python-based models) for timeline & factor extraction.	Claims management, documentation analysis, and dispute timeline mapping.	Extracted timeline events and 26 influencing factors from contract correspondence; demonstrated how NLP can speed claim resolution and highlight documentation gaps.

JCBM (2025) 8(S1) 30-47

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

The Influence of Technical and Non-Technical Emergency Response Systems on Infrastructure Resilience

Haruna Domanamwin Abudu[1], Cecilia Modupe Mewomo[2], Kofi Owusu Adjei[3] and Francis Kwesi Bondinuba[4]

[1]Department of Construction Management and Quantity Surveying, Durban University of Technology, South Africa
[2]Department of Engineering Technology, Tarleton State University, USA
[3]Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa
[3&4]Department of Construction Technology and Quantity Surveying, Kumasi Technical University, Ghana
[4]Faculty of Engineering and the Built Environment, Durban University of Technology, South Africa
[4]The Urban Institute, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, UK

Received 03 October 2025; received in revised form 19 December 2025, 25 December 2025; accepted 27 December 2025
https://doi.org/10.15641/jcbm.8.S1.1923

Abstract

This study evaluates the impact of Emergency Response Systems (ERS) on infrastructure resilience in the Ashanti Region of Ghana using a quantitative research approach. A questionnaire survey was administered to 225 professionals, including facility managers, engineers, architects, building inspectors, and NADMO officials, yielding 159 valid responses. The data were analysed using descriptive statistics, such as means and standard deviations, and exploratory factor analysis and partial least squares structural equation modelling. The findings indicate that both technical and non-technical ERSs significantly affect infrastructure resilience, with nine technical and seven non-technical ERSs receiving high performance ratings. Economic factors, such as property damage, and socio-political issues, including low wages, were closely linked to ERS effectiveness. Key challenges identified included inadequate consideration of cultural factors, limited institutional capacity, and insufficient funding. These challenges were strongly influenced by technical ($\beta = 0.223$, $p < 0.05$) and non-technical ($\beta = 0.462$, $p < 0.05$) ERS elements. Consequently, these limitations affected economic ($\beta = 0.195$, $p < 0.05$) and socio-political ($\beta = 0.325$, $p < 0.05$) outcomes, highlighting the interdependence between ERS components and broader systemic resilience. In practice, the study emphasises the need for integrated ERS planning within broader institutional, legal, and socio-economic systems by government agencies and facility managers. It advocates for targeted technological investments, legal frameworks, community education, and long-term risk management strategies. This study presents a novel interdisciplinary framework that integrates engineering and policy perspectives. Its originality lies in the comprehensive assessment of both technical and non-technical ERS components, offering valuable insights for strengthening infrastructure resilience in developing contexts.

Keywords: Emergency response, Disaster, Facilities, Infrastructure resilience, Natural hazard.

1. Introduction

Emergency Response Systems (ERS) face growing challenges due to rising population levels and increasing natural and human-made hazards, which threaten lives, property, and community stability (Vinokurova *et al*., 2022; Zulu & Shi, 2023; Abudu *et al*., 2025a/b). Most infrastructure supports vital services such as transport, energy, and education (Sharma & Gardoni, 2018). Urbanisation increases population density in buildings, thereby raising vulnerability during emergencies (Matveev *et al*., 2021). Congested access points to facilities further exacerbate safety risks and delay emergency responders, underscoring the need for proactive disaster risk management (DRM) strategies (Khalid *et al*., 2021). Effective crowd control during evacuations is critical, as panic-induced behaviour can lead to severe injuries (Yazdi & Zarei, 2024; Adjei *et al*., 2025). Fires remain a major risk globally, with varying

[1] Corresponding Author
Email address: 22494813@dut4life.ac.za

levels of regulatory effectiveness; incidents such as the Grenfell Tower fire in London expose critical weaknesses in emergency response mechanisms (Zualkernan *et al*., 2019). In Ghana, frequent fire outbreaks continue to cause loss of life and significant economic damage, reinforcing the urgency of strengthening all phases of DRM to improve public safety outcomes (Zulu & Shi, 2023).

Recent studies have examined nature-based solutions for improving emergency preparedness in Africa (Aghimien *et al*., 2024), the socio-economic impacts of veld fires (Adom *et al*., 2025), and climate resilience within smart city frameworks (Mallick, 2025). While these studies advance knowledge on risk mitigation and resilience, limited empirical attention has been given to how technical and non-technical ERS components jointly influence infrastructure resilience in sub-Saharan Africa, particularly from an integrated systems perspective. Moreover, existing studies often emphasise the importance of ERS without quantitatively disentangling the relative contributions of technological capacity, institutional arrangements, governance structures, and socio-cultural factors.

To address this gap, this study applies partial least squares structural equation modelling (PLS-SEM) to examine the complex relationships between technical and non-technical ERS elements and infrastructure resilience outcomes in the Ashanti Region of Ghana. The novelty of this study lies in its development of an integrated analytical framework that simultaneously evaluates technical systems and non-technical institutional and socio-cultural factors, thereby moving beyond confirmation of ERS relevance to reveal how and to what extent specific ERS components shape resilience performance.

Accordingly, the study is guided by the following research questions:

RQ1: What technical and non-technical ERS components significantly influence infrastructure resilience in Ghana?

RQ2: What challenges limit the effectiveness of emergency response systems in infrastructure resilience?

RQ3: How do technical and non-technical ERS elements interact to affect economic and socio-political resilience outcomes?

2. Literature Review

2.1. Overview of Emergency Response Systems

An Emergency Response System (ERS) is a coordinated framework for managing disasters and other emergencies by integrating technical, institutional, and human components (Wang *et al*., 2022). Its effectiveness is central to reducing fatalities, protecting assets, and enabling rapid recovery, thereby directly contributing to overall community and infrastructure resilience (Dwarakanath *et al*., 2021). Risk management is a core function of ERS and involves hazard identification, vulnerability assessment, exposure analysis, and strategic resource allocation to safeguard people and infrastructure (Perera *et al*., 2020). Exposure reflects the degree to which people and assets are at risk, while hazard characteristics and environmental conditions guide appropriate risk reduction measures.

Technological advancements have significantly enhanced ERS capabilities. Tools such as surveillance cameras, sensors, geographic information systems, and data analytics improve disaster detection, situational awareness, and early warning dissemination (Damaševičius *et al*., 2023). These technologies support rapid decision-making and coordinated response, particularly in complex urban and facility environments.

Beyond technology, data management and community involvement are widely recognised as critical enablers of effective ERS. Institutions, including governmental agencies, religious bodies, and civil society organisations, play key roles in collecting and analysing disaster-related data to inform preparedness and response strategies (Sutton *et al*., 2024). Forecasting tools utilise environmental data to predict hazard events, while social media and digital platforms enable rapid dissemination of alerts and public information (Sibiya, 2022). Public briefings, drills, and training programmes help translate warnings into actionable responses, and religious and social groups often support awareness creation and emergency training at the community level (Sutton *et al*., 2024).

Preparedness for emergencies within facilities requires collaboration among local communities, professional stakeholders, and communication experts to translate national disaster risk reduction (DRR) policies into context-specific actions (Perera *et al*., 2020). Investments in early warning systems, resilient infrastructure, and grassroots initiatives are therefore essential. Education and awareness programmes further enhance resilience by strengthening social networks and collective response capacity (Cvetković *et al*., 2021).

Assessing ERS capacity typically involves evaluating technical, organisational, and human resource dimensions, including the availability of tools such as GPS, drones, and thermal cameras (Damaševičius *et al*., 2023; Cvetković *et al*., 2021). However, empirical studies show that early warning systems often fail to trigger timely action due to weak institutional coordination or insufficient training (Perera *et al*., 2020), and overreliance on technology without adequate human capacity can create communication gaps (Kalogiannidis *et al*., 2022). Effective disaster response, therefore, requires coordinated action among government institutions, emergency services, and the public (Gilmore & DuRant, 2021).

Despite growing awareness, urban planning and social housing sectors continue to face resource and capacity gaps that undermine emergency preparedness (Travassos *et al*., 2021). Disaster risk management (DRM) increasingly relies on cross-sector collaboration, encompassing risk assessment, mitigation, preparedness, response, and financing mechanisms (Bello *et al*., 2021). While integrating DRM into national development policies improves coordination, Flood Early Warning Systems (FEWS) still face challenges related to community engagement and local ownership (Perera *et al*., 2020). Social media has emerged as a valuable tool for rapid crisis communication and can be effectively applied in facility-based emergency management (Dwarakanath *et al*., 2021).

Cities increasingly embed climate adaptation and resilience objectives into development plans to align with DRR and DRM priorities (Anguelovski *et al*., 2014). The World Meteorological Organisation's impact-based forecasting approach further strengthens hazard management by linking forecasts to potential consequences (Merz *et al*., 2020). In facility management, smart technologies support hazard detection, early warnings, and data-driven emergency decision-making. However, non-technical aspects of ERS, such as collaboration, communication, governance, and community participation, remain persistent challenges, particularly in developing-country contexts (Perera *et al*., 2020; Myeong *et al*., 2020).

2.2. Emergency Response Systems and Their Influence on Infrastructure and Facility Resilience

In this study, infrastructure resilience refers to the ability of interconnected physical systems such as buildings, transport networks, utilities, and essential services to withstand, absorb, recover from, and adapt to disruptive events.

Facility resilience, by contrast, focuses more narrowly on the performance and recovery of individual buildings or complexes within the broader infrastructure system. While conceptually distinct, both are interdependent, and effective ERS plays a critical role in enhancing resilience at both levels.

Globally, disasters impose substantial human and economic costs. Between 2001 and 2018, floods accounted for more than half of water-related disasters, causing approximately 94,000 deaths and USD 504 billion in losses worldwide (Perera *et al*., 2020). Integrating early warning systems with impact-based forecasting has been shown to enhance emergency response effectiveness through improved data-driven insights (Merz *et al*., 2020). Economic conditions strongly influence disaster frequency, severity, and recovery capacity, with disasters causing significant loss of life and financial resources (Bello *et al*., 2021).

From 2010 to 2019, natural disasters resulted in average annual losses exceeding USD 187 billion and displaced approximately 24 million people per year. While high-income countries have reduced disaster impacts through robust ERS and institutional capacity, low- and middle-income countries such as Ghana continue to face significant DRM challenges (Mensah-Bonsu, 2022). Vulnerable populations often experience disproportionate impacts due to insecure housing, limited access to services, and weak recovery mechanisms, further undermining infrastructure and facility resilience.

The socio-economic impacts of disasters are commonly assessed using context-specific indicators such as hazard frequency, exposure levels, and population density (Merz *et al*., 2020). The 2010 Pakistan floods, for example, severely damaged homes, infrastructure, healthcare facilities, and schools, exposing weaknesses in institutional coordination and long-term recovery planning (Deen, 2015). Despite extensive relief efforts, resilience outcomes remained limited, highlighting the importance of effective ERS beyond immediate response.

Disaster risks continue to threaten community sustainability by disrupting economic activities, social systems, and development trajectories (Tanesab, 2020). Internal migration from rural to urban areas further exacerbates exposure and increases pressure on public facilities and infrastructure, particularly in rapidly urbanising regions (Mensah-Bonsu, 2022).

Figure 1 illustrates the conceptual structure of ERS and its associated challenges and impacts, providing a basis for examining the interrelationships tested in this study.

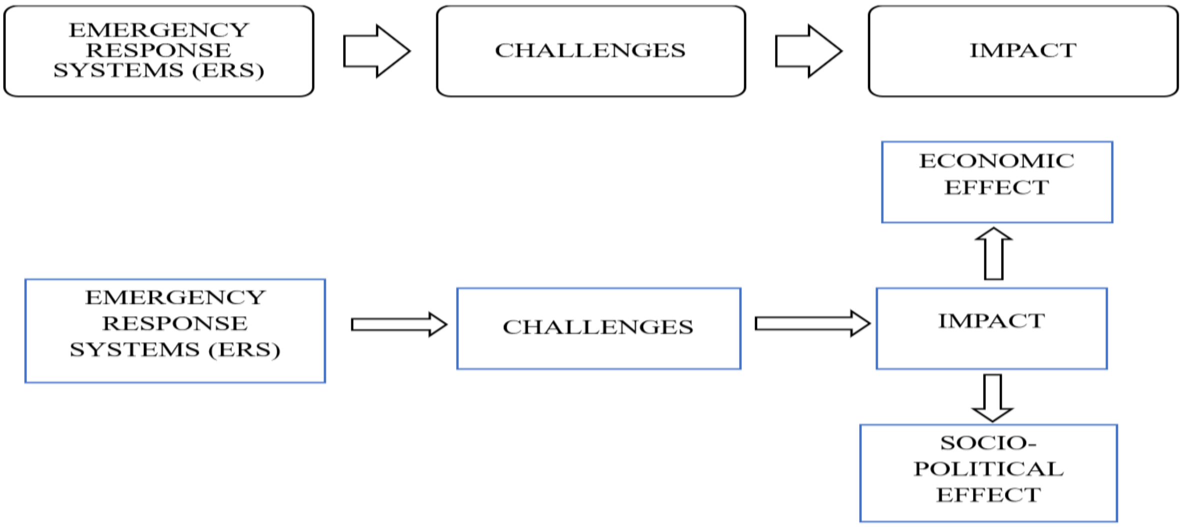

Figure 1: Conceptualised Emergency Response System
Source: Abudu *et al.* (2025b)

2.3. Research Model and Hypotheses

The reviewed literature highlights a consistent theme: infrastructure and facility resilience are shaped by the interaction between technical ERS components (e.g., monitoring, communication, data systems) and non-technical components (e.g., governance, institutional capacity, community engagement, and policy enforcement). However, many existing studies examine these elements in isolation or focus primarily on confirming the importance of ERS rather than empirically analysing their interrelationships.

This gap directly informs the development of the study's structural equation modelling (SEM) framework. Drawing on the reviewed evidence, the study hypothesises that:

1. Technical ERS components significantly influence emergency response challenges.

2. Non-technical ERS components exert a more substantial and more systemic influence on these challenges;

3. Emergency response challenges, in turn, significantly affect economic and socio-political resilience outcomes.

By explicitly modelling these relationships using PLS-SEM, the study advances the literature by quantifying the pathways through which ERS components affect infrastructure resilience, particularly in sub-Saharan Africa.

2.4. Theories underpinning the study

Resilient ERS frameworks are grounded in systems theory and resilience theory, both of which emphasise interconnectedness, feedback mechanisms, and adaptive capacity (Bonaretti & Piccoli, 2018; Chen *et al*., 2017). Systems theory provides a holistic perspective for understanding interactions among technological, institutional, and social subsystems. In contrast, resilience theory focuses on a system's ability to absorb shocks, recover, and adapt to changing conditions. Together, these theories offer a robust foundation for analysing complex emergency response environments that rely on both technical and non-technical ERS components (Son *et al*., 2020).

3. Research Methodology

This study adopted a quantitative research approach to develop a framework for modernising emergency response infrastructure in Ghana. Data were collected through structured questionnaires administered to 225 professionals, including facility managers, engineers, architects, building inspectors, and officials from the National Disaster Management Organisation (NADMO), across 43 districts in the Ashanti Region. The target population comprised 516 professionals involved in facility planning and disaster response. A sample size of 225 respondents was determined using Yamane's formula. Purposive and convenience sampling techniques were employed to access respondents with relevant professional expertise who were easily accessible.

Data was collected using a structured questionnaire designed on a 5-point Likert scale. Responses were cleaned, coded, and normalised using Min–Max scaling prior to analysis. Descriptive statistics, such as means and standard deviations, and an Exploratory Factor Analysis (EFA) were conducted using the Statistical Package for the Social Sciences (SPSS) version 30. EFA was performed using Principal Component Analysis (PCA) with Varimax rotation to identify underlying factor structures. The suitability of the data for factor analysis was assessed using the Kaiser–Meyer–Olkin (KMO) measure (≥ 0.6) and Bartlett's test of sphericity ($p < 0.05$). Factors with eigenvalues ≥ 1 and factor loadings ≥ 0.5 were retained. Internal consistency reliability was assessed using Cronbach's Alpha coefficients, with values ≥ 0.7 considered acceptable.

Following the descriptive analysis, Min–Max normalisation was applied to rank indicators by their relative importance. Indicators with a normalisation value (NV) ≥ 0.60 were classified as key indicators. This threshold enabled the model to focus on the most salient and consistently rated indicators while maintaining construct content validity, as further supported by prior factor analysis and expert review.
Structural Equation Modelling (SEM) was conducted using a variance-based Partial Least Squares approach implemented in SmartPLS 4 (Ringle *et al*., 2024). This method was selected due to its suitability for exploratory research, complex models, and non-normal data distributions. Model reliability, validity, and predictive relevance were assessed using established PLS-SEM criteria.

Content validity was ensured through expert review of the questionnaire, while construct validity was established through factor analysis. The inclusion of respondents from diverse professional backgrounds enhanced the analytical robustness of the findings. Ethical standards were strictly observed, with participation being voluntary and anonymous to ensure confidentiality. The study adhered to Institutional Review Board requirements and received ethical approval under clearance number IREC 287/24.

4. Findings and Discussion

The analysis followed three stages: descriptive analysis, normalisation, and PLS-SEM. Descriptive analysis summarised indicator ratings, while normalisation identified key variables.

4.1. Descriptive Statistics and Normalisation of the Constructs' Indicators

This section summarises descriptive statistics in Tables 1-3 for the emergency response system, response challenges, and their economic and socio-political impacts. Mean scores, standard deviations, and normalised values were used to rank indicators, with those scoring ≥ 0.60 considered key contributors.

The study identified nine (9) TERS indicators in Table 1 (See Appendix 1) with high ratings (NV: 1.00–0.649; mean: 4.30–4.12), and low standard deviations (<1.00), indicating consistent responses. The key indicators included disaster monitoring, communication networks, traffic and crime surveillance, risk analysis, and data management. Seven NTERS were also highly rated (NV: 1.00–0.608; mean: 4.18–3.91) with strong consistency. Key areas included policy enforcement, capacity building, risk reduction planning, loss assessment, rescue communication, social inclusion, and investment in risk reduction.

4.2. Discussion on the Technical Emergency Response System and Its Impact on Infrastructure Resilience

The key technical emergency response system (TERS) variables were ranked using mean effectiveness, standard deviation, normalised value (NV), and importance, reflecting the relative contribution of essential technologies to effective emergency management and infrastructure resilience. Disaster Monitoring emerged as the most critical construct (Mean = 4.30; NV = 1.000), underscoring its foundational role in detecting hazards and initiating timely response actions. This finding aligns with Bello *et al*. (2021), who emphasised that real-time disaster monitoring systems enhance early warning capabilities, reduce response delays, and significantly minimise damage to critical infrastructure. Practically, facility managers and government agencies should prioritise investments in sensor-based monitoring, satellite surveillance, and integrated alert systems to strengthen preparedness and response capacities.

Communication and Networking of Disaster ranked second (Mean = 4.27; NV = 0.947), reinforcing the importance of seamless information flow among emergency responders, institutions, and affected populations. This result corroborates the findings of Damaševiˇcius *et al*. (2023), who demonstrated that interoperable communication platforms improve coordination and reduce fragmentation during emergencies. From an implementation perspective, this highlights the need for unified communication protocols, resilient digital networks, and redundancy measures to ensure uninterrupted information exchange during crises.

Traffic Monitoring (Mean = 4.27; NV = 0.936) was also identified as a critical determinant of infrastructure resilience. Consistent with Myeong *et al*. (2020), the results show that smart traffic management systems enhance situational awareness, facilitate efficient evacuations, and ensure unobstructed access for emergency vehicles. Actionably, integrating traffic monitoring technologies into urban transport systems can improve evacuation planning and reduce congestion-related delays during emergencies.

Recognising and Analysing Disaster Risk (Mean = 4.24; NV = 0.894) highlights the growing relevance of predictive analytics and modelling tools in proactive risk management. This supports the assertions of Damaševiˇcius *et al*. (2023) that data-driven risk analysis strengthens preparedness by enabling scenario planning and targeted mitigation strategies.

Infrastructure planners can apply these tools to identify vulnerabilities and prioritise reinforcement measures before disasters occur.

Monitoring of Street Security (Mean = 4.23; NV = 0.872) and Crime Watch Monitoring Systems, including CCTV and drones (Mean = 4.21; NV = 0.819), further demonstrate the convergence of public safety and disaster response technologies. These findings align with Myeong *et al*. (2020), who noted that surveillance systems improve real-time decision-making and maintain order during crises. In practice, integrating security monitoring into ERS can support crowd management, protect emergency assets, and reduce secondary risks such as looting or vandalism.

Data Management and Analysis of Disaster (Mean = 4.19; NV = 0.787) reinforces the role of structured data systems in supporting evidence-based decision-making. As noted by Damaševiˇcius *et al*. (2023), effective data management enhances coordination, learning, and continuous improvement of emergency response strategies. Agencies should therefore establish centralised disaster data platforms to support timely analysis and institutional learning.

Risk Assessment of Disaster (Mean = 4.17; NV = 0.755) and Risk Identification (Mean = 4.12; NV = 0.649), although ranked lower, remain integral to resilience planning. These findings are consistent with Mensah-Bonsu (2022) and Perera *et al*. (2020), who highlighted that systematic risk identification and assessment underpin prevention and preparedness strategies. Practically, embedding routine risk assessments into infrastructure lifecycle planning can enhance adaptive capacity and long-term resilience.

4.3. Discussion on Non-Technical Emergency Response System Constructs and Their Impact on Infrastructure Resilience

While TERSs are critical for immediate response, the findings confirm that non-technical emergency response systems (NTERSs) play a decisive role in shaping long-term infrastructure resilience by addressing governance, institutional capacity, and social dimensions of disaster risk management (DRM). Enforcement and Translation of Disaster Risk Policies ranked highest among NTERS constructs (Mean = 4.18; NV = 1.000), underscoring the importance of translating policy frameworks into actionable, enforceable measures. This result supports Perera *et al.* (2020), who argued that weak policy implementation undermines resilience outcomes despite well-articulated DRR strategies. Actionably, strengthening enforcement mechanisms, monitoring compliance, and clarifying institutional roles can bridge the gap between policy intent and on-ground practice.

Capacity Building in DRR and DRM across Institutions, Organisations, and Communities (Mean = 4.03; NV = 0.792) underscores the importance of human capital development in resilience-building. This finding aligns with Cvetkovi'c *et al*. (2021), who emphasised that training, education, and institutional readiness enhance decentralised and sustainable emergency response systems. Practically, continuous professional development programmes and community-based training initiatives can improve preparedness at multiple governance levels.

DRR Plans and Platforms for Cities or Communities (Mean = 4.03; NV = 0.784) highlight the need for localised, context-specific resilience strategies. Consistent with Damaševiˇcius *et al*. (2023), the results suggest that tailored DRR platforms improve urban planning, hazard mapping, and resource allocation. Policymakers and planners can leverage these platforms to integrate local risk profiles into broader development and infrastructure planning processes.

Assessment of Damage and Losses for Resilient Rebuilding (Mean = 3.98; NV = 0.712) highlights the significance of post-disaster evaluation in supporting effective recovery. This finding supports Sutton *et al*. (2024) and Mensah-Bonsu (2022), who noted that accurate damage assessments enable the integration of resilience principles into reconstruction efforts. Practically, adopting standardised assessment frameworks can improve transparency and guide investment towards “build-back-better” outcomes.

Communication and Networking Between Rescue Teams and Victims (Mean = 3.97; NV = 0.704) addresses the human and relational dimensions of emergency response. In line with Damaševiˇcius *et al*. (2023), the results indicate that effective communication enhances trust, situational awareness, and operational efficiency. Implementing inclusive communication channels, including multilingual and accessible platforms, can improve engagement with affected populations.

Gender and Social Inclusiveness in DRR Management (Mean = 3.95; NV = 0.672) reflects the growing recognition that resilience depends on equitable participation. This finding is consistent with Perera *et al*. (2020) and Sutton *et al*. (2024), who stressed that excluding vulnerable groups weakens overall resilience. In practice, mainstreaming gender and social inclusion into DRR policies and programmes can ensure that diverse needs are addressed in both the planning and response phases.

Although investing in DRR for Resilience at the national and Local Levels ranked lowest (Mean = 3.91; NV = 0.608), it remains fundamental to sustainable resilience outcomes. As noted by Bello *et al*. (2021), long-term investment in infrastructure, education, early warning systems, and risk mitigation provides the foundation for effective ERS performance.

Governments should therefore prioritise sustained financing mechanisms to support both technical and non-technical resilience-building initiatives.

4.4. Descriptive Statistics of Emergency Response Impact

Economic impact indicators showed strong perceived effects of the emergency response system, with mean scores from 4.27 to 4.15 (Table 2). Three indicators, loss of properties (4.27; SD=0.818), loss of life (4.26; SD=0.743), and global economic losses (4.24; SD=0.787), met the normalisation threshold (≥0.60). Socio-political indicators also scored high (4.19 to 3.94) with consistent responses, and four low wages, increased vulnerability, lack of social amenities, and rising unemployment, met the threshold.

Table 2: Descriptive Statistics of Emergency Response Impact

Code	Emergency Response Impact	Mean	Std. Dev.	NV	Rank
Economic Impact					
EIE3	Loss of properties	4.27	0.818	1.000**	1
EIE2	Loss of lives	4.26	0.743	0.909**	2
EIE1	Global economic losses	4.24	0.787	0.727**	3
EIE4	Inadequate residential infrastructure	4.19	0.851	0.318	4
EIE5	Inadequate health care facilities	4.15	0.815	0.000	5
Socio-Political Impact					
SIE6	Low salaries and wages	4.19	0.831	1.000**	1
SIE3	Increase in vulnerability	4.18	0.799	0.955**	2
SIE2	Lack of social amenities	4.17	0.797	0.932**	3
SIE4	Increase in unemployment rate	4.13	0.787	0.773**	4
SIR5	Low productivity	3.97	0.893	0.114	5
SIE1	Population density and urbanisation	3.94	0.973	0.000	6

Source: Fieldwork, 2025

** Normalisation value greater than 0.60

4.5. Discussion on the Economic Impact of Emergency Response Systems and their Influence on Infrastructure Resilience

Economic impacts constitute a critical dimension of Emergency Response Systems (ERS), as they directly influence infrastructure resilience, recovery capacity, and long-term development outcomes. This study assessed loss of properties, loss of life, and global economic losses using mean scores, standard deviations, normalised values (NV), and rankings, highlighting the severity of disaster-related economic disruptions and the importance of effective ERS interventions.

Loss of Properties emerged as the most significant economic impact (Mean = 4.27; NV = 1.000), reflecting widespread recognition of the extensive material and infrastructural damage caused by disasters. This finding is consistent with Bello *et al.* (2021) and Abudu *et al.* (2025a), who reported that damage to buildings, utilities, transport networks, and essential services generates cascading economic effects, including business interruptions and increased reconstruction costs. From a practical standpoint, this result underscores the need for ERS to be integrated with risk-sensitive land-use planning, enforcement of resilient building standards, and proactive maintenance of critical infrastructure to minimise property losses during emergencies.

Loss of Life followed closely (Mean = 4.26; NV = 0.909), emphasising the profound human and economic consequences of inadequate disaster preparedness. Although often categorised as a social impact, the loss of human capital significantly affects labour productivity, household income, and the trajectories of national economic recovery. This result aligns with the findings of Bello *et al.* (2021), Mensah-Bonsu (2022), and Abudu *et al.* (2025b), who demonstrated that high mortality rates during disasters undermine workforce stability and slow post-disaster economic recovery.
Actionably, this highlights the importance of strengthening early warning systems, improving response times, and ensuring inclusive evacuation and sheltering strategies to protect lives and sustain economic resilience.

Global Economic Losses (Mean = 4.24; NV = 0.727), although ranked third, remain highly significant. These losses reflect disruptions to global supply chains, reduced foreign direct investment, inflationary pressures, and GDP contractions, particularly in disaster-prone developing economies. This finding corroborates earlier studies by Bello *et al.* (2021), Mensah-Bonsu (2022), and Abudu *et al.* (2025a), which emphasised that recurrent disasters amplify macroeconomic instability. The result suggests that national governments should prioritise investment in robust ERS and regional cooperation mechanisms to reduce the spillover effects of disasters on global and regional economies.

4.6. *Discussion on the Socio-Political Impact of Emergency Response Systems (ERS) and Their Influence on Infrastructure Resilience*

Socio-political factors play a decisive role in shaping ERS effectiveness and infrastructure resilience by influencing vulnerability, response capacity, and recovery outcomes. This study evaluated key socio-political variables using mean scores, standard deviations, normalised values (NV), and rankings, revealing how underlying social and political conditions mediate ERS performance.

Low Salaries and Wages ranked highest (Mean = 4.19; NV = 1.000), indicating their critical influence on individual, institutional, and community resilience. Inadequate income limits households' ability to invest in preparedness measures, recover from losses, or adopt adaptive strategies. It also constrains institutions' capacity to attract, motivate, and retain skilled emergency response personnel. This finding aligns with Abudu *et al*. (2025a/b), who highlighted the link between income insecurity and reduced disaster coping capacity. From an implementation perspective, improving remuneration structures and social protection schemes can enhance both workforce stability and community resilience.

Increase in Vulnerability (Mean = 4.18; NV = 0.955) highlights the compounding effects of socio-economic inequality, poor housing conditions, and limited access to education and healthcare. Consistent with Merz *et al*. (2020), Bello *et al*. (2021), and Abudu *et al*. (2025c), the results show that vulnerable populations disproportionately suffer from infrastructure failures and experience slower recovery. Actionably, this underscores the importance of targeted ERS interventions, such as risk-informed social protection programmes and community-based preparedness initiatives, to reduce differential vulnerability.

Lack of Social Amenities (Mean = 4.17; NV = 0.932), including healthcare facilities, clean water supply, transportation systems, and educational infrastructure, significantly undermines community resilience. This finding supports Merz *et al*. (2020) and Bello *et al*. (2021), who noted that inadequate access to basic services increases dependency on external assistance during disasters and prolongs recovery periods. In practice, strengthening social infrastructure and integrating essential services into emergency planning can improve response effectiveness and resilience.

The increase in the Unemployment Rate (Mean = 4.13; NV = 0.773) represents both a driver and a consequence of weak infrastructure resilience. Disasters frequently disrupt livelihoods, displace workers, and damage economic assets, leading to job losses. Persistent unemployment further reduces households' ability to invest in preparedness or adaptation measures. This finding aligns with Merz *et al*. (2020), Bello *et al*. (2021), and Abudu *et al*. (2025a). Actionably, post-disaster recovery programmes that prioritise job creation, skills development, and livelihood restoration can strengthen socio-economic resilience and support sustainable infrastructure recovery.

4.7. *Descriptive Statistics of Emergency Response Challenges*

The challenges associated with the emergency response system revealed nine indicators with high normalisation values (≥ 0.60). From the results, the mean scores of these indicators (Table 3) ranged from 4.22 to 3.98, with relatively low standard deviations, indicating high consistency in ratings.

Table 3: Descriptive Statistics of Emergency Response Challenges

Code	Emergency Response Challenges	Mean	Std. Dev.	NV	Rank
CHG14	Inadequate consideration of social, cultural, and religious norms and practices in emergency response infrastructure.	4.22	0.788	1.000**	1
CHG11	Lack of knowledge or capacity	4.17	0.831	0.922**	2
CHG8	Inadequate institution/organisation	4.12	0.880	0.835**	3
CHG13	Lack of capacity building	4.10	0.898	0.809**	4
CHG1	Rapid urbanisation and population growth	4.06	0.946	0.748**	5
CHG10	Lack of human resources	4.06	0.916	0.748**	6
CHG2	Limited resources and funding	4.01	1.028	0.661**	7
CHG7	Ineffective building by-laws	3.99	1.170	0.643**	8
CHG9	Policy/legal issues	3.98	0.912	0.626**	9
CHG12	Lack of community engagement	3.95	0.886	0.574	10
CHG3	Vulnerability to natural disasters	3.94	1.079	0.557	11
CHG6	Political influence	3.91	1.137	0.504	12
CHG5	Inadequate infrastructure	3.79	1.083	0.322	13
CHG4	Lack of technology	3.58	1.157	0.000	14

Source: Fieldwork, 2025

** Normalisation value greater than 0.60

4.8. Discussion on Emergency Response Challenges and Their Implications for Infrastructure Resilience

Identifying the constraints on Emergency Response Systems (ERS) is essential to strengthening infrastructure resilience and improving disaster response effectiveness. As presented in Table 3, the study categorised these challenges into institutional, socio-cultural, and structural dimensions. It ranked them using mean scores, standard deviations, normalised values (NV), and levels of significance. The findings reveal that non-technical and governance-related barriers exert a substantial influence on ERS performance, reinforcing the need for systemic, context-sensitive interventions.

Inadequate consideration of social, cultural, and religious norms emerged as the most critical challenge (Mean = 4.22), indicating a significant disconnect between emergency planning frameworks and local community contexts. This finding aligns with Abudu *et al*. (2025a) and Wamsler *et al*. (2020), who argued that emergency interventions that overlook cultural and religious practices often face resistance, low compliance, and reduced effectiveness. In practice, incorporating culturally sensitive engagement strategies, such as involving traditional leaders, faith-based organisations, and community influencers, can improve trust, participation, and cooperation during emergency preparedness and response efforts.

Lack of knowledge or capacity (Mean = 4.17) highlights deficiencies in human capital and technical expertise that limit preparedness and response capabilities. Consistent with Abudu *et al*. (2025b) and Wamsler *et al*. (2020), this result underscores how insufficient skills and awareness contribute to delayed response and ineffective coordination. Actionable implications include investing in continuous professional training for emergency personnel and community education programmes to enhance disaster literacy and preparedness at the grassroots level.

Inadequate institutions (Mean = 4.12) reflect systemic weaknesses in governance structures, inter-agency coordination, and accountability mechanisms. This finding supports earlier work by Abudu *et al*. (2025b) and Wamsler *et al*. (2020), which identified institutional fragmentation as a significant obstacle to effective disaster risk management. Strengthening institutional frameworks through more explicit mandates, improved coordination platforms, and performance monitoring systems can enhance ERS efficiency and infrastructure resilience.

The lack of capacity building (Mean = 4.10) further underscores the need for sustained investment in education, training, and organisational development. As noted by Abudu *et al*. (2025a) and Wamsler *et al*. (2020), capacity-building initiatives are critical for developing adaptive skills and enabling local actors to respond effectively to evolving risks. Practically, embedding capacity-building programmes within national and local DRM strategies can support long-term resilience outcomes.

Rapid urbanisation and population growth (Mean = 4.06) place increasing pressure on existing infrastructure and emergency services, thereby amplifying disaster risks. This finding is consistent with Wamsler *et al*. (2020) and Abudu *et al*. (2025b), who highlighted the need for risk-sensitive urban development to manage growing exposure. Integrating ERS considerations into urban planning, zoning regulations, and infrastructure expansion can help mitigate the adverse effects of rapid urban growth.

Insufficient human resources (Mean = 4.06) further constrain emergency response effectiveness by limiting operational capacity during crises. In line with Kalogiannidis *et al*. (2022) and Abudu *et al*. (2025c), the results indicate that staffing shortages increase response times and reduce service coverage. Addressing this challenge requires strategic workforce planning, improved recruitment and retention policies, and incentives for emergency response professionals.

Limited resources and funding (Mean = 4.01) represent a persistent barrier, particularly in low- and middle-income countries. This finding corroborates Abudu *et al*. (2025a) and Kalogiannidis *et al*. (2022), who emphasised that inadequate financing restricts technological upgrades, training, and infrastructure maintenance. Actionably, diversifying funding sources, strengthening public–private partnerships, and prioritising disaster risk reduction investments can improve ERS sustainability.

Ineffective building by-laws (Mean = 3.99) highlight regulatory shortcomings that increase infrastructure vulnerability. Consistent with Abudu *et al*. (2025a), Abdul and Yu (2020), and Wamsler *et al*. (2020), outdated or weakly enforced building codes expose communities to higher risks. Regularly updating building regulations and enforcing compliance can significantly enhance structural resilience and reduce disaster-related losses.

Finally, policy and legal issues (Mean = 3.98) reveal gaps in legislative clarity, enforcement, and political commitment. This finding aligns with Abudu *et al*. (2025a/b), who noted that weak legal frameworks undermine coordinated emergency response. Strengthening legal instruments, clarifying institutional responsibilities, and ensuring sustained political support are therefore essential for effective ERS implementation and resilient infrastructure development.

4.9. Partial Least Squares Structural Equation Modelling

PLS-SEM was used to estimate relationships between latent variables using a reflective approach. The analysis included evaluations of the measurement and structural models. The reflective measurement model was assessed by evaluating indicator loadings per SEM guidelines (Hair *et al*., 2016). All items were treated as reflective indicators. Reliability was confirmed via Cronbach's alpha and composite reliability (Hair *et al*., 2019), and indicator reliability was assessed via factor loadings.

Convergent validity was confirmed by AVEs above 0.50 (Fornell & Larcker, 1981). Discriminant validity was assessed via the HTMT ratio and the Fornell-Larcker criterion (Henseler *et al*, 2015), confirming conceptual and empirical distinctiveness. Results appear in Figure 2 and Tables 4 and 5.

4.10. Reliability and Convergent Validity of the Model

Table 4 (See Appendix 1) confirms the model's reliability and validity. Factor loadings (0.716–0.928) showed strong indicator-construct associations. Path coefficients and indicator weights reinforced these links. Bootstrapping (5,000 samples) produced t-values above 1.96 at the 5% level, confirming high and significant loadings and supporting item reliability. Internal consistency was confirmed with composite reliability (0.821–0.930) and Cronbach's alpha (0.889–0.944), exceeding the 0.70 threshold. AVE values (0.612–0.770) surpassed the 0.50 benchmark, indicating strong convergent validity and that constructs explained over half the variance in their indicators (Hair *et al*., 2016).

4.11. Discriminant Validity Statistics

Discriminant validity was confirmed using the HTMT and Fornell-Larcker criteria. HTMT values were all below the 0.85 threshold (max = 0.480), indicating strong validity (Voorhees *et al*., 2016; Hair *et al*., 2019). Similarly, Fornell-Larcker results showed all AVE square roots exceeded inter-construct correlations, further supporting discriminant validity (Table 5).

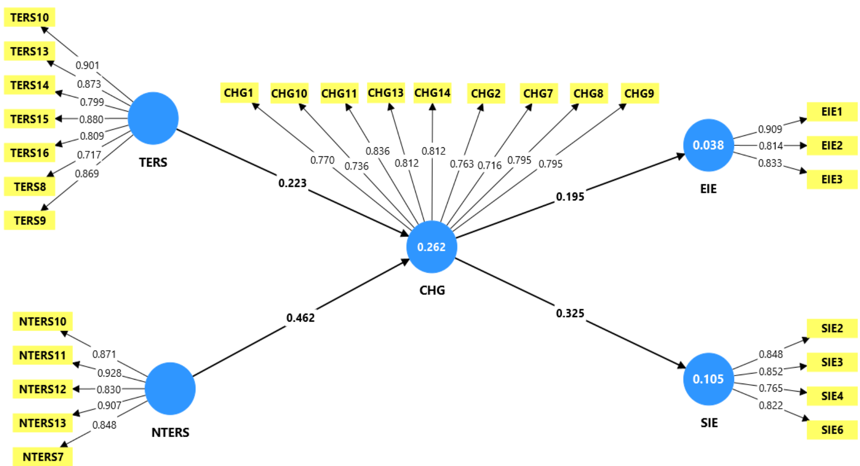

Figure 2: Measurement Model Diagram
Source: Fieldwork, 2025

Table 5: Discriminant Validity Statistics

	CHG	EIE	NTERS	SIE	TERS
Heterotrait-Monotrait (HTMT) Ratio	-				
CHG					
EIE	0.203				
NTERS	0.480	0.240			
SIE	0.365	0.393	0.244		
TERS	0.216	0.084	0.067	0.192	-
Fornell-Larcker criterion	-				
CHG	**0.782**				
EIE	0.195	**0.853**			
NTERS	0.460	0.216	**0.878**		
SIE	0.325	0.352	0.225	**0.822**	
TERS	0.220	-0.011	-0.006	0.164	**0.837**

Source: Fieldwork, 2025

4.12. Path Analysis and Predictive Relevance

The structural model was assessed after confirming measurement model adequacy. Key evaluation criteria included R^2, Q^2, path coefficients, and statistical significance. The R^2 values for challenges (0.262), economic impact (0.038), and socio-political impact (0.105) indicate varying levels of explained variance. Q^2 values revealed small predictive relevance for economic and socio-political impacts and moderate relevance for challenges.

Path analysis (Table 6) shows that all structural relationships are positive. Higher scores on the technical and non-technical emergency response system constructs indicate stronger ERS capacity. In comparison, higher scores on the challenges construct reflect greater recognition and reporting of response constraints. Consequently, the positive paths from TERS → CHG ($\beta = 0.223$; $p < 0.05$) and NTERS → CHG ($\beta = 0.462$; $p < 0.05$) suggest that contexts with more developed ERS capacities are more likely to identify and articulate operational, institutional, and governance-related challenges, potentially due to higher organisational awareness and diagnostic capability.

While the relationships are statistically significant, the low R^2 values for economic and socio-political impacts indicate limited explanatory power. These results should therefore be interpreted as indicative rather than strongly predictive, highlighting the likelihood that additional contextual factors such as governance quality, macroeconomic conditions, and broader development dynamics also shape these outcomes.

allocation. This finding is consistent with Abudu *et al.* (2025a), who reported that inadequate technological infrastructure constrains situational awareness and coordination during disaster events. From a practical perspective, the result underscores the need for sustained investment in interoperable technologies, regular system maintenance, and redundancy planning to reduce technical bottlenecks and enhance response effectiveness.

More notably, the non-technical ERS dimension, which encompasses policy enforcement, institutional capacity, governance structures, and community engagement, exerts an even stronger influence on emergency response challenges. The path coefficient of 0.462, together with a t-value of 7.882 and a p-value < 0.05, indicates a robust, highly significant relationship. This suggests that weaknesses in governance arrangements, institutional coordination, and stakeholder engagement substantially intensify the challenges faced during emergency response operations. This finding aligns with Abudu *et al.* (2025b), who emphasised that deficiencies in governance and institutional capacity undermine the effectiveness of emergency responses regardless of the availability of advanced technologies. The results suggest that policymakers and emergency managers should prioritise strengthening institutional frameworks, enforcing disaster risk reduction policies, and expanding community-based capacity-building programmes to complement technical system investments.

The analysis further reveals that emergency response challenges have a significant downstream effect on economic outcomes during and after disaster events. With a path coefficient of 0.195 ($t = 2.708$; $p < 0.05$), the findings confirm that ineffective emergency response systems contribute to heightened economic losses, including property damage, business disruption, and increased recovery expenditures. This result supports the findings of Abudu *et al.* (2025c) and Bello *et al.* (2021), who demonstrated that delayed or poorly coordinated emergency responses exacerbate economic vulnerability and prolong recovery processes. Practically, strengthening both technical and non-technical ERS components can serve as a proactive economic risk mitigation strategy by reducing direct

Table 6: Path Analysis and Predictive Relevance

	Path Coefficient	Sample Coefficient	Std. Dev.	t-value	P values	Confidence Interval		f-square
						2.5%	97.5%	
CHG -> EIE	0.195	0.212	0.072	2.708	0.007	-0.073	0.312	0.039
CHG -> SIE	0.325	0.333	0.068	4.762	0.000	0.177	0.443	0.118
NTERS -> CHG	0.462	0.463	0.059	7.882	0.000	0.335	0.565	0.289
TERS -> CHG	0.223	0.231	0.065	3.446	0.001	0.109	0.331	0.067

Source: Fieldwork, 2025

4.13. Discussion of the emergency response system and its relationships

The results demonstrate that technical emergency response system (ERS) components, such as disaster monitoring, communication networks, and traffic surveillance, have a statistically significant influence on the magnitude of challenges encountered during emergencies. The positive and significant path coefficient ($\beta = 0.223$; $t = 3.446$; $p < 0.05$) indicates that deficiencies in the development, integration, and maintenance of technical ERS components are associated with increased operational challenges, including delayed response times, ineffective information exchange, and inefficient resource losses and limiting indirect economic impacts.

Beyond economic consequences, the study also establishes a significant relationship between emergency response challenges and socio-political outcomes. The observed path coefficient of 0.325 ($t = 4.762$; $p < 0.05$) indicates that persistent emergency response challenges exacerbate socio-political stresses, including unemployment, inequitable access to services, and declining public confidence in institutions. This finding is consistent with Abudu *et al.* (2025b) and Bello *et al.* (2021), who highlighted that ineffective disaster management erodes social cohesion and weakens trust in governance systems. From an implementation standpoint, this underscores the importance of inclusive, transparent, and community-sensitive emergency planning processes that actively engage stakeholders and promote institutional accountability.

The findings reinforce the interdependent nature of technical and non-technical emergency response system components and their collective influence on economic and socio-political resilience. Achieving sustainable infrastructure resilience, therefore, requires an integrated ERS approach that balances technological innovation with strong governance arrangements, institutional capacity, and meaningful community participation.

Unlike the authors' previous review-based studies (Abudu *et al.*, 2025a–c), which synthesised conceptual and qualitative insights, this study provides empirical evidence on the relative influence of technical and non-technical ERS components using PLS-SEM. The findings empirically confirm earlier qualitative assertions regarding the centrality of governance and institutional capacity, while also revealing the limited explanatory power of ERS variables for economic and socio-political outcomes, thereby identifying critical gaps for future quantitative research.

5. Conclusions

This study examined the influence of technical and non-technical emergency response systems (TERS and NTERS) on infrastructure resilience, providing empirical evidence on how their interaction shapes resilience outcomes across technical, institutional, economic, and socio-political dimensions.

Key empirical contributions of the study can be summarised as follows:

- Among technical ERS domains, early warning and disaster monitoring systems, communication networks, and real-time data analytics emerged as the most critical contributors to infrastructure resilience, particularly in enhancing response speed, coordination, and adaptive capacity.
- Non-technical ERS domains, notably governance capacity, institutional coordination, community engagement, and inclusive planning, demonstrated a strong enabling effect, amplifying the performance and Sustainability of technical systems.
- The findings indicate that while TERS have a more immediate and measurable impact on operational resilience, NTERS exert a significant complementary influence, particularly on long-term recovery, adaptability, and equitable outcomes.
- The combined implementation of TERS and NTERS yields greater resilience gains than isolated investments, reinforcing the need for integrated emergency response strategies.

Despite these contributions, the study is subject to several methodological limitations that constrain the generalisability of the findings. The findings are limited by the use of non-probability sampling and a single regional focus. In addition, the low R^2 values indicate that the model explains only a limited proportion of infrastructure resilience, suggesting that other factors beyond those examined in this study may also play a role. Significantly, this study advances the existing literature by empirically demonstrating that infrastructure resilience is not solely a function of technological sophistication but also depends on institutional effectiveness, economic preparedness, and socio-political inclusiveness. By integrating economic risk considerations into ERS design, decision-makers can reduce long-term recovery costs, safeguard livelihoods, and sustain economic continuity. Similarly, addressing socio-political dimensions such as equity, access to resources, and participatory governance strengthens the legitimacy and effectiveness of emergency response systems.

Future research should build on these findings by employing probability-based sampling, multi-regional or cross-country comparisons, and longitudinal designs to capture resilience dynamics over time. Further work is also needed to develop robust metrics for operationalising socio-political and economic factors within ERS frameworks. From a policy and practice perspective, the results underscore the need for coordinated investments in both technical capabilities and governance structures to achieve resilient, adaptive, and inclusive infrastructure systems.

References

Abdul, L. and Yu, T. F. (2020) 'Resilient urbanisation: a systematic review on urban discourse in Pakistan', *Urban Science*, 4(4), p. 76. https://doi.org/10.3390/urbansci4040076

Abudu, H. D., Mewomo, C. M., Adjei, K. O. and Bondinuba, F. K. (2025a) 'A systematic review of the mitigating factors for emergency response in facilities', *CIB Conferences*, 1(1), p. 187. https://doi.org/10.7771/3067-4883.1856

Abudu, H. D., Mewomo, C. M., Adjei, K. O. and Bondinuba, F. K. (2025b) 'Assessing emergency response systems and their impact on infrastructure resilience: A literature review'. In Abimbola Windapo (ed.) *Proceedings of the International Conference on Construction Business & Project Management Conference 2025 (CBPMC)*, University of Cape Town, South Africa, pp. 425-431. Available at: https://cbpmconference.wixsite.com/website-6/copy-of-cbpm-editions-1(Accessed: 01//09/2025).

Abudu, H. D., Mewomo, C. M., Adjei, K. O., & Bondinuba, F. K. (2025c) 'Challenges in Emergency Response Infrastructure: A Systematic Literature Review'. *Journal of Civil Engineering, Science and Technology*, 16(2), 269–279. https://doi.org/10.33736/jcest.8972.2025. Retrieved from https://publisher.unimas.my/ojs/index.php/JCEST/article/view/8972

Adjei, K. O., Abudu, H. D., Nana-Addy, E. and Musonda, I. (2025) 'The motivation for occupants' adoption of hidden emergency exits in buildings'. *Engineering, Construction and Architectural Management*, 32(13), pp.133-147. https://doi.org/10.1108/ECAM-04-2023-0326

Adom, R. K., Makananisa, T. and Simatele, M. D. (2025) 'Assessing social, economic and environmental challenges of veld fires in South Africa: A case study of Capricorn District Municipality in Limpopo Province', *Journal of Sustainable Forestry*, pp. 1-24.

Aghimien, D., Aliu, J., Chan, D. W., Aigbavboa, C. and Awuzie, B. (2024) 'Making a case for nature-based solutions for a sustainable built environment in Africa', *Sustainable Development*. https://doi.org/10.1108/SASBE-11-2023-0353

Anguelovski, I., Chu, E. and Carmin, J. (2014) 'Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South', *Global Environmental Change*, 27, pp. 156-167. https://doi.org/10.1016/j.gloenvcha.2014.05.010

Bello, O., Bustamante, A. and Pizarro, P. (2021) 'Planning for disaster risk reduction within the framework of the 2030 Agenda for Sustainable Development'.

Bonaretti, D. and Piccoli, G. (2018) 'Effective use of information systems for emergency management: a representation theory perspective', *39th International Conference on Information Systems*, San Francisco.

Chen, W., Zhai, G., Fan, C., Jin, W. and Xie, Y. (2017) 'A planning framework based on system theory and GIS for urban emergency shelter system: A case of Guangzhou, China', Human and Ecological Risk Assessment: *An International Journal*, 23(3), pp. 441-456. https://doi.org/10.1080/10807039.2016.1185692

Cvetković, V. M., Tanasić, J., Ocal, A., Kešetović, Ž., Nikolić, N. and Dragašević, A. (2021) 'Capacity development of local self-governments for disaster risk management', *International Journal of Environmental Research and Public Health*, 18(19), p. 10406. https://doi.org/10.3390/ijerph181910406

Damaševičius, R., Bacanin, N. and Misra, S. (2023) 'From sensors to safety: Internet of Emergency Services (IoES) for emergency response and disaster management', *Journal of Sensor and Actuator Networks*, 12(3), p. 41. https://doi.org/10.3390/jsan12030041

Deen, S. (2015) 'Pakistan 2010 floods. Policy gaps in disaster preparedness and response, *International Journal of Disaster Risk Reduction*, 12, pp. 341-349. https://doi.org/10.1016/j.ijdrr.2015.03.007

Dwarakanath, L., Kamsin, A., Rasheed, R. A., Anandhan, A., and Shuib, L. (2021) 'Automated machine learning approaches for emergency response and coordination via social media in the aftermath of a disaster: A review', *IEEE Access*, 9, pp. 68917-68931. https://doi.org/10.1109/ACCESS.2021.3074819

Fornell, C. G. and Larcker, D. F. (1981) 'Evaluating structural equation models with unobservable variables and measurement error', *Journal of Marketing Research*, 18(1), pp. 39-50. https://doi.org/10.1177/002224378101800104

Gilmore, J. N. and DuRant, M. (2021) 'Emergency infrastructure and locational extraction: Problematising computer-assisted dispatch systems as a public good', *Surveillance & Society*, 19(2), pp. 187-198. https://doi.org/10.24908/ss.v19i2.14116

Hair Jr, J. F., Hult, G. T. M., Ringle, C. and Sarstedt, M. (2016). A primer on partial least squares structural equation modelling (PLS-SEM). *Thousand Oaks, CA*: Sage Publications.

Hair, J. F., Hult, G. T. M., Ringle, C. M. and Sarstedt, M. (2019) A primer on partial least squares structural equation modelling (PLS-SEM), *2nd edn. Thousand Oaks, CA*: Sage Publications. https://doi.org/10.3926/oss.37

Henseler, J., Ringle, C. M. and Sarstedt, M. (2015) 'A new criterion for assessing discriminant validity in variance-based structural equation modelling', *Journal of the Academy of Marketing Science,* 43(1), pp. 115-135. https://doi.org/10.1007/s11747-014-0403-8

Kalogiannidis, S., Toska, E., Chatzitheodoridis, F. and Kalfas, D. (2022) 'Using school systems as a hub for risk and disaster management: A case study of Greece', *Risks*, 10(5), p. 89. https://doi.org/10.3390/risks10050089

Khalid, M., Awais, M., Singh, N., Khan, S., Raza, M., Malik, Q. B. and Imran, M. (2021) 'Autonomous transportation in emergency healthcare services: framework, challenges, and future work', *IEEE Internet of Things Magazine*, 4(1), pp. 28-33. https://doi.org/10.1109/IOTM.0011.2000076

Mallick, R. (2025) 'Smart Cities and Climate Resilience', in Community Resilience and Climate Change Challenges: Pursuit of Sustainable Development Goals (SDGs), *IGI Global Scientific Publishing*, pp. 401-412. https://doi.org/10.4018/979-8-3693-6522-9.ch021

Matveev, A. V., Maximov, A. V. and Zadurova, A. A. (2021) 'Simulation model of emergency evacuation in case of fire in a nightclub', *in IOP Conference Series: Earth and Environmental Science*, 720(1), p. 012019. IOP Publishing. https://doi.org/10.1088/1755-1315/720/1/012019

Mensah-Bonsu, E. (2022) 'A critical review of the disaster management system in Ghana', ADRRI *Journal (Multidisciplinary)*, 31(2/8), pp. 88-110.

Merz, B., Kuhlicke, C., Kunz, M., Pittore, M., Babeyko, A., Bresch, D. N., … and Wurpts, A. (2020) 'Impact forecasting to support emergency management of natural hazards', *Reviews of Geophysics*, 58(4), e2020RG000704. https://doi.org/10.1029/2020RG000704

Myeong, S., Kim, Y. and Ahn, M. J. (2020) 'Smart city strategies: technology push or culture pull? A case study exploration of Gimpo and Namyangju, South Korea, *Smart Cities*, 4(1), p. 41. https://doi.org/10.3390/smartcities4010003

Perera, D., Agnihotri, J., Seidou, O. and Djalante, R. (2020) 'Identifying societal challenges in flood early warning systems', *International Journal of Disaster Risk Reduction*, 51, p. 101794. https://doi.org/10.1016/j.ijdrr.2020.101794

Ringle, C. M., Wende, S. and Becker, J.-M. (2024). SmartPLS 4. Bönningstedt: SmartPLS. Available at: https://www.smartpls.com (Accessed: 01/09/2025).

Sharma, N. and Gardoni, P. (2018) 'Modelling the time-varying performance of electrical infrastructure during post-disaster recovery using tensors', *in Routledge Handbook of Sustainable and Resilient Infrastructure*, pp. 263-282. Routledge. https://doi.org/10.4324/9781315142074-14

Sibiya, G. N. (2022). Information and Communication Technology in Disaster Preparedness by eThekwini Municipality (Doctoral dissertation).

Son, C., Sasangohar, F., Neville, T., Peres, S. C. and Moon, J. (2020) 'Investigating resilience in emergency management: An integrative review of literature', *Applied Ergonomics*, 87, p. 103114. https://doi.org/10.1016/j.apergo.2020.103114

Sutton, J., Olson, M. K. and Waugh, N. A. (2024) 'The Warning Lexicon: A multiphased study to identify, design, and develop content for warning messages', *Natural Hazards Review*, 25(1), p. 04023055. https://doi.org/10.1061/NHREFO.NHENG-1900

Tanesab, J. P. (2020) 'Institutional effectiveness and inclusions: Public perceptions on Indonesia's disaster management authorities', *International Journal of Disaster Management*, 3(2), pp. 1-15. https://doi.org/10.24815/ijdm.v3i2.17621

Travassos, L., Torres, P. H. C., Di Giulio, G., Jacobi, P. R., Dias De Freitas, E., Siqueira, I. C. and Ambrizzi, T. (2021) 'Why do extreme events still kill in the São Paulo Macro Metropolis Region? Chronicle of a death foretold in the global South', *International Journal of Urban Sustainable Development*, 13(1), pp. 1-16. https://doi.org/10.1080/19463138.2020.1762197

Vinokurova, L., Solovyeva, V. and Filippova, V. (2022) 'When ice turns to water: Forest fires and indigenous settlements in the Republic of Sakha (Yakutia)', *Sustainability*, 14(8), p. 4759. https://doi.org/10.3390/su14084759

Voorhees, C. M., Brady, M. K., Calantone, R. and Ramirez, E. (2016) 'Discriminant validity testing in marketing: an analysis, causes for concern, and proposed remedies', *Journal of the Academy of Marketing Science*, 44(1), pp. 119-134. https://doi.org/10.1007/s11747-015-0455-4

Wamsler, C., Wickenberg, B., Hanson, H., Olsson, J. A., Stålhammar, S., Björn, H. and Zelmerlow, F. (2020) 'Environmental and climate policy integration: Targeted strategies for overcoming barriers to nature-based solutions and climate change adaptation', *Journal of Cleaner Production*, 247, p. 119154. https://doi.org/10.1016/j.jclepro.2019.119154

Wang, H., Ye, H., Liu, L. and Li, J. (2022) 'Evaluation and obstacle analysis of emergency response capability in China', *International Journal of Environmental Research and Public Health*, 19(16), p. 10200. https://doi.org/10.3390/ijerph191610200

Yazdi, M. and Zarei, E. (2024) 'Enhancing crowd safety resilience through systematic analysis', in Progressive Decision-Making Tools and Applications in Project and Operation Management: Approaches, Case Studies, Multi-criteria Decision-Making, Multi-objective Decision-Making, Decision under Uncertainty, Cham: Springer Nature Switzerland, pp. 221-240. https://doi.org/10.1007/978-3-031-51719-8_14

Zualkernan, I. A., Aloul, F. A., Sakkia, V., Al Noman, H., Sowdagar, S. and Al Hammadi, O. (2019) 'An IoT-based emergency evacuation system', *in 2019 IEEE International Conference on Internet of Things and Intelligence System (IoTaIS), IEEE*, pp. 62-66. https://doi.org/10.1109/IoTaIS47347.2019.8980381

Zulu, E. and Shi, Y. (2023) 'Fire risk analysis and resilience improvement in Lusaka city', *Journal of Emergency Management and Disaster Communications*, 4(02), p. 119-141. https://doi.org/10.1142/S2689980923500082

Appendix 1

Table 1: Descriptive Statistics of Emergency Response System

Code	Technical Emergency Response System (TERS)	Mean	Std. Dev.	NV	Rank
TERS10	Disaster monitoring.	4.30	0.884	1.000**	1
TERS13	Communication and networking of disasters.	4.27	0.871	0.947**	2
TERS9	Traffic monitoring.	4.27	0.901	0.936**	3
TERS15	Recognising and analysing disaster risk.	4.24	0.978	0.894**	4
TERS8	Monitoring of street security.	4.23	0.891	0.872**	5
TERS11	Crime watch monitoring systems (eg, CCTV and drones).	4.21	0.895	0.819**	6
TERS14	Data management and analysis of disasters.	4.19	0.932	0.787**	7
TERS16	Risk assessment of disaster.	4.17	0.902	0.755**	8
TERS2	Risk identification.	4.12	0.892	0.649**	9
TERS1	Understanding disaster risk in its dimensions.	4.08	0.930	0.574	10
TERS7	Environmental conditions of risk.	4.06	0.964	0.543	11
TERS17	Community engagement in monitory disaster.	4.03	0.974	0.489	12
TERS23	Predicting trends of disaster occurrence for DRR management actions.	4.01	0.963	0.447	13
TERS3	Vulnerability of risk factor.	3.98	1.054	0.394	14
TERS6	Hazard characteristics of risk.	3.98	1.019	0.383	15
TERS19	Creation of a system for the prediction of disaster events.	3.97	0.971	0.372	16
TERS20	Data management and analysis of past and present disasters for DRR and DRM.	3.97	0.769	0.362	17
TERS22	Identifying problems associated with pre-disaster management measures.	3.94	0.830	0.319	18
TERS5	Exposure of risk.	3.92	1.000	0.277	19
TERS18	Religious institution involvement in monitoring disasters.	3.92	1.016	0.277	20
TERS4	Capacity of risk factor.	3.91	1.037	0.255	21
TERS21	Assessing the current situation of disaster occurrence for DRR and DRM.	3.83	0.896	0.096	22
TERS12	Provision of monitoring devices and sensors.	3.78	1.086	0.000	23
	Non-Technical Emergency Response System (NTERS)				
NTERS10	Enforcement translation of disaster risk policies.	4.18	0.916	1.000**	1
NTERS13	Capacity building in DRR and DRM in various institutions, organisations, and communities.	4.03	1.246	0.792**	2
NTERS12	DRR plan and platforms for various cities or communities.	4.03	1.070	0.784**	3
NTERS21	Assessment of damage and losses for resilient rebuilding of DRR plan and strategies.	3.98	0.865	0.712**	4
NTERS17	Communication and networking between rescue teams and victims in disaster situations for effective, sound rescue.	3.97	0.960	0.704**	5
NTERS7	Gender and social inclusiveness in DRR and DRM.	3.95	1.004	0.672**	6
NTERS11	Investing in DRR for resilience at both national and local levels.	3.91	1.204	0.608**	7
NTERS15	Inclusive of religious and social institutions in DRR and DRM.	3.89	1.049	0.592	8
NTERS8	Institutional communication and awareness in DRR.	3.89	0.909	0.584	9
NTERS24	Resilient public investment for post-disaster.	3.89	0.957	0.584	10
NTERS9	Community participation in DRM.	3.88	1.159	0.576	11
NTERS3	Creation of a database for easy accessibility of risk information and ease of communication.	3.88	1.001	0.568	12
NTERS2	Institutions' and organisations' awareness of pre-disaster	3.87	0.963	0.560	13

	information for DRM.				
NTERS1	Social media broadcasting of disaster information for readiness and preparedness.	3.87	1.011	0.552	14
NTERS16	Rescue of lives and properties by emergency responders in the event of a disaster.	3.84	1.020	0.512	15
NTERS18	Provision of devices and sensors for speedy detection and rescue of victims in emergencies.	3.82	1.037	0.488	16
NTERS23	Multi-stakeholders' coordination for post-disaster recovery plans, policies, and implementation.	3.82	0.948	0.480	17
NTERS19	Setting an optimal search-and-rescue plan for DRR and DRM at the national and local levels.	3.77	1.103	0.416	18
NTERS6	Stakeholders' cooperation for DRM.	3.77	1.251	0.408	19
NTERS22	Planning for resilient reconstruction and rehabilitation for post-disaster recovery.	3.74	0.912	0.368	20
NTERS20	Creation of assessment measures for post-disaster event(s) for resilience measures.	3.72	1.095	0.336	21
NTERS14	Inclusive DRR in the educational curriculum.	3.71	1.227	0.320	22
NTERS26	Adaptation Measures of DRR and DRM.	3.59	1.082	0.152	23
NTERS25	Planning for a resilient recovery for post-disaster	3.57	1.104	0.120	24
NTERS5	Involvement of religious and social institutions in the pre-disaster stage for effective DRR.	3.54	1.032	0.088	25
NTERS4	Platformization of early warning systems in various cities, institutions, and communities.	3.48	1.126	0.000	26

Source: Fieldwork, 2025

** Normalisation value greater than 0.60.

Table 4: Reliability and Convergent Validity of the Model

	Loadings	t-value	CA	CR	AVE
TERS8	0.717	6.586	0.930	0.942	0.701
TERS9	0.869	11.441			
TERS10	0.901	11.725			
TERS13	0.873	11.086			
TERS14	0.799	7.902			
TERS15	0.880	11.377			
TERS16	0.809	10.672			
NTERS7	0.848	24.913	0.925	0.944	0.770
NTERS10	0.871	25.151			
NTERS11	0.928	87.395			
NTERS12	0.830	26.759			
NTERS13	0.907	64.548			
CHG1	0.770	17.542	0.921	0.934	0.612
CHG2	0.763	19.903			
CHG7	0.716	13.886			
CHG8	0.795	20.211			
CHG9	0.795	26.069			
CHG10	0.736	16.179			
CHG11	0.836	28.505			
CHG13	0.812	24.204			
CHG14	0.812	20.503			
EIE1	0.909	9.059	0.821	0.889	0.728
EIE2	0.814	6.443			
EIE3	0.833	6.874			
SIE2	0.848	20.790	0.840	0.893	0.676
SIE3	0.852	26.469			
SIE4	0.765	13.355			
SIE6	0.822	17.933			

Source: Fieldwork, 2025

CA: *Cronbach's alpha*
CR: *Composite reliability*
AVE: *Average variance extracted*

JCBM (2025) 8(S1) 48-61

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Port Efficiency: The Application of Blockchain Technology in the Construction Material Supply Chain

Adeola Oluwatoyin Osundiran[1] and Makgopa Tshehla[2]

[1&2]Graduate School of Business Leadership, Sustainable Livelihood, University of South Africa, South Africa

Received 05 October 2025; received in revised form 19 October 2025, 18 December 2025; accepted 27 December 2025
https://doi.org/10.15641/jcbm.8.S1.1924

Abstract

The Port of Durban has recently experienced operational delays, which have affected its performance. Delays at the Port hinder the timely completion of projects in South Africa's construction sector. Hence, this exploratory research focuses on identifying, through the literature, the suitability and consequences of using blockchain technology to facilitate the supply chain for construction materials. Furthermore, the port productivity of the Port of Durban was compared with that of Rotterdam harbours. The Quantitative Research Approach aligns with this research philosophy and underpinnings. Secondary data are collected from the port website, and the Malmquist Productivity Index is used to determine the enablers of Port Productivity from 2017 to 2023. The heterogeneity of the port cases limits the generalisation of findings. However, policymakers, project managers, investment planners, and operational practitioners will benefit as the possibilities of blockchain technology in enhancing the supply chain of construction materials are discussed. Due to time constraints, the data is limited to the period of 2017-2023. The research findings show that technologies such as Blockchain and artificial intelligence are major drivers of port productivity at the Port of Rotterdam. The application of various customised technologies has improved the Port of Rotterdam's productivity. The construction sector is in dire need of effective, efficient port systems, given the multiple stakeholders and projects. The application of Blockchain technology, especially with smart contracts, provides a degree of flexibility.

Keywords: Blockchain, Construction Material Supply Chain, Efficiency, Productivity, Port of Durban and Rotterdam.

1. Introduction

Operational delays are a recurring phenomenon at Durban Harbour, affecting its performance. According to the World Bank CPPI (2023), the harbours of Cape Town, Durban, and Port Elizabeth in South Africa have been ranked among the world's worst-performing container ports. Griessel (2024) states that along the shores of Durban and Richards Bay in South Africa, almost 100 cargo vessels, laden with fuel, bulk dry goods, containers, and cars, are held up due to delays attributed to a combination of adverse weather conditions and ageing terminal equipment. The implications of port congestion for the construction sector, including the challenges it poses, include a rapid increase in material and labour costs (Griessel, 2024). Delays at the Port can adversely affect the timely completion of construction projects in South Africa (Nemakhavhani & Khafiso, 2024). This is known as time overruns in the construction sector—specifically, delays attributed to the importation of construction materials.

The implications of bottlenecks at the Port have a multiplier effect not only on the Construction sector but also on the South African economy as a whole. One of the significant research gaps that this study seeks to bridge is the fragmentation in the construction supply chain. This exploratory study focuses on identifying, through the literature, the application of blockchain technology (BCT) to facilitate the supply chain for construction materials. Hence, BCT serves as a tool for the seamless flow of information and documentation amongst the stakeholders. Furthermore, the research also focuses on the enablers of port productivity for both the Durban and Rotterdam harbours. Rotterdam harbour is used as a benchmark because of its proven excellence in applying various 4IR Technologies, such as Blockchain. Soni & Smallwood (2023) opine that the construction sector is crucial to South Africa's growth

[1] Corresponding Author
Email address: osundo@unisa.ac.za

and development, contributing to infrastructure development, among other areas. The construction industry creates employment and promotes economic development. As ongoing construction points to environmental and societal dynamism, so too does port efficiency serve as a significant parameter for the successful management of the construction material supply chain (Obasi et al., 2024). Nikjow et al. (2021) also attest that one of the major causes of delays in the procurement of construction materials is inefficient logistics and supply chain. An inefficient port should consider other options, such as Blockchain Technology, to expedite the entire process. Bottlenecks at the Port have a multiplier effect not only on the Construction sector but also on the South African economy as a whole. Leah (2024) further elaborates by citing examples that can affect construction materials supply chains, such as shortages, supply chain disruptions, inflation, and delays due to cumbersome customs procedures. According to Meersman et al. (2012), a Port is congested when it cannot meet the demand of port users at the quayside, crane, yardside, or gate.

Congestion is a significant hindrance to international trade and economic development, particularly during the COVID-19 pandemic (Lin, Zeng, Luo, and Nan, 2022). Yen and Mulley (2023) attest that the more ports understand the importance of efficiency in port operations, the more they can improve their resource allocation and productivity. Vessels laden with containers have their operations expedited in developed economies due to quick clearance times, the adoption of technological architecture, and increased labour output (UNCTAD, 2023). Herein lies the importance of blockchain technology. Blockchain technology can be used to streamline sea-going operations by enhancing customs clearance processes across various shipping containers (Wang et al., 2021). The study is inclined toward the use of secondary data extracted from the respective port websites; hence, a quantitative research design. Kao (2023) states that efficiency is calculated as the proportion of output to input. For this study, inputs include container berths, tug boats, terminals, cranes, port employees, and the length of the quay, whilst the outputs are the number of vessel visits to the harbour and container throughput. Ports are adversely affected by procedural complexities, redundancy, and unintegrated information and document flows, which affect various port users and stakeholders involved in seaport operations (Mthembu & Chasomeris, 2024). According to the USDA Report (2024), South African ports have experienced chronic and acute operational challenges over the years. Analysts estimated that during the peak of the port challenges, the collective economic impact of slowdowns exceeded R124 billion (approximately US$6.5 billion) per day (USDA, 2024). The following are the research objectives of the study:

- Literary thematic identification of the application of a shared distributed digital ledger (BCT) in facilitating the value chain of construction materials.
- Determine the enablers of port productivity for the Durban and Rotterdam harbours.
- Compare the various applications of technology at the Port of Durban and the Port of Rotterdam.

The following is the outline of the paper: Section 2 reviews peer-reviewed journal articles and book chapters; Section 3 examines methodological approaches; Section 4 discusses the results; and Section 5 elaborates on the conclusion and recommendations.

2. Literature Review

The Port has a pivotal role in the Global Supply Chain (Li et al., 2025). Guan *et al*. (2024) note the critical role of ports in promoting global trade and commerce, as well as their adaptability, flexibility, and performance through the lens of 4IR technologies such as artificial intelligence, Blockchain, and the Internet of Things. BCT, also known as a shared, distributed, digital ledger, has gained prominence due to its relevance to the industry (Guan *et al.,* 2024). Blockchain-based approaches could solve the manipulation and fraud issues of export certificates in these areas. In addition, the distributed and immutable ledger can prevent the export of counterfeit or stolen goods (Böhmecke-Schwafert, 2024). This section examines the concepts that underpin this study. These are the construction sector, the Port, port efficiency, the implication of port inefficiency, and the application of a shared distributed digital ledger.

2.1. The Importance of the Construction Industry

No nation can be transformed from a state of development to full development without the effective functioning of its construction sector. According to the Department of Trade, Industry, and Competition (2024), the construction industry is a significant catalyst for socio-economic development because, as a critical employer of labour, it contributes 5.3% and 7.8% of South Africa's formal and informal sector employment, respectively.

2.2. Construction Material Supply Chain

Ghamari et al. (2024) posit that the Construction Material Supply Chain is a network series that shows how construction materials are imported from origin to destination. In this sector, the supply chain manager plays a critical role in strategically planning the consignment from the harbour of origin to the final harbour, the destination. For instance, South Africa imports steel from America and Cement from China. Other imported construction materials include sand, gravel, crushed stone, Plywood, Hardboard, Pine, eucalyptus transmission poles, and Industrial electrical cables (South African Iron and Steel Institute, 2025). South Africa's main trading partners include China, the United States, Germany, and Japan. Steel is a critical material in the construction sector (Putri & Firmansyah, 2020). According to Putri and Firmansyah (2020), Steel is a unique and critical construction material that serves as a raw material for roofing sheets, beams, and columns.

2.3. The Port

The Port is the gateway to any nation's economy, with the port authority serving as the gatekeepers. Tovar and Alan (2024) affirm the importance of Ports, stating that Ports cannot be sidelined in the development of modern economies, as they serve as gateways to hinterlands and hubs and provide specialised services for the energy and cruise-based tourism sectors. This further reiterates that the Port serves as a platform to enhance international trade. The Port is the bedrock for generating domestic and foreign revenue for countries. Peng, Bai, Yang, Yuen, and Wu (2023) affirm that the Ports are central to the maritime supply chain. The implication of this is that without the Port, the maritime supply chain is spineless and scattered. Ayesu and Boateng (2024) posit that Ports are pivotal in facilitating international trade and economic development, hence serving as vital corridors for the movement of goods across the African continent and beyond. Not only are ports of essential value to the global supply chain, but their productivity is also critical. Therefore, seaports and their efficiency remain essential for the success of global international trade (Ayesu, Sakyi & Baidoo, 2024). Mazibuko et al. (2024) assert that a container port's competitiveness depends on the productivity of its container terminal. Continuous monitoring and evaluation of ports ensure risks are mitigated, and crucial decisions are made promptly.

2.3.1. The South African Ports

Over 80% of South Africa's international trade is done by sea (International Trade Administration-ITA, 2024). The South African harbours, including Saldanha, Cape Town, Coega, Mossel Bay, Port Elizabeth, East London, Durban, and Richards Bay, are pivotal to importation and exportation (Transnet, 2024). However, poor infrastructure, a poor maintenance culture, faulty equipment, and wind are major issues plaguing port operations (USDA, 2024).

2.3.2. The Port of Rotterdam

The World Shipping Council (2022) states that the Port of Rotterdam is ranked 10th among the top 60 container ports globally and is the largest Port in Europe. Port of Rotterdam website (2024) asserts that the Port of Rotterdam is deliberate and committed to digitisation and port efficiency. According to Farah et al. (2024), the Port of Rotterdam has used blockchain technology since 2016 to facilitate the tracking and tracing of container shipments of flowers. The service enables a seamless flow of information with customs authorities, thereby allowing exporters to track fully and trace shipments (Farah et al., 2024).

2.3.3. Port Efficiency and Congestion

Yen and Mulley (2023) state that transport efficiency is critical. The evaluation of port performance primarily aims to improve port operations and provide useful information for port development planning and strategies (Suárez-Alemán et al., 2016). When a Port is efficient, it is obvious because there are few delays across its various operational levels. The operational areas include the quayside, crane, yard, and gate operations. A very good parameter to measure port efficiency is the absence of delays at the Port of entry or exit. According to the Port of Rotterdam (2024), an efficient port offers short turnaround and berthing times for vessels, seamless documentation procedures, and high customer satisfaction. According to Pallis and Rodrigue (2022), Port efficiency is multidimensional and describes operational performance, with an emphasis on maximising output and minimising costs. Efficiency drives port competitiveness (Danladi et al., 2024). According to Danladi et al. (2024), various indices, including delays and congestion, indicate that ports are inefficient. On the Durban coastal lines, many vessels are often waiting to berth. The Port is congested and lacks the capacity to handle all vessels. This is a sign of capacity and operational constraints.

2.4. Blockchain Technology (BCT)

According to Farah et al. (2024), Blockchain technology is a credible and essential solution to enhance security, transparency, and efficiency in the maritime industry, where the increasing reliance on digital systems and data is prevalent. According to Monrat et al. (2019), Blockchain has the following features: decentralisation, immutability, transparency, and auditability. These features make transactions more secure and tamper-proof (Monrat, Schelén, and Andersson, 2019). Ziga and Turk (2017) state that the construction value chain includes multiple stakeholders; hence, BCT can provide a trustworthy framework for sharing vital documents, information, and transactions. A predominant feature of the maritime supply chain is a prolonged operational process, structures, and complex data and knowledge generated by multiple stakeholders (Liu et al., 2021). This feature serves as an impetus for the adoption of blockchain technology. The emerging blockchain technology has the characteristics of decentralisation, tamper-proofing, and traceability, which can be correctly applied in the construction material maritime supply chain to promote its transformation and upgrading (Liu et al., 2021).

2.5. Taxonomy of the Significance of Blockchain in the Construction Sector

The search strategy for developing Table 1 (See Appendix 1) used the Google Scholar database for the period 2015-2025. The keywords were "Blockchain Technology Application" and "Construction Sector". The inclusion criteria were articles that demonstrate the importance of blockchain technology in construction. Based on the scoping review search criteria, 20 peer-reviewed articles were selected from the literature to examine the significance of blockchain technology in the construction sector. The table displays the various significance of Blockchain applications in ports.

2.6. Themes

Based on the taxonomy, four major themes are critical to the research gap. Four themes emerged from the review: managing stakeholders in the construction materials supply chain; traceability and transparency; data security; and efficiency and smart contracts.

2.6.1. Managing Stakeholders in Construction Materials Supply Chain

Several stakeholders are involved in the supply chain for construction materials. The stakeholders include the port authority, the freight forwarder, the project management team, and many others. Now, due to the complexity of the entire import and export process, these stakeholders can end up working in silos. Kiu et al. (2020) state that blockchain technology improves loose collaboration amongst the stakeholders. This further fragments the process and increases project costs. Žiga and Klinc (2017) and Okanlawon et al. (2025) purport that blockchain technology improves the construction process.

2.6.2. Traceability and Transparency

Who does what, when, and how is critical in the construction material supply chain. One theme that emerged from scoping the literature review is that Blockchain facilitates traceability and transparency. This is supported by Figueiredo et al. (2024) and Nasih et al. (2024). A container load of construction material can be tracked from the Port of origin to the Port of destination. Elmay et al. (2022) affirm the application of blockchain technology in monitoring the supply chain process.

2.6.3. Data security

The large volume of data being shared amongst stakeholders requires significant trust. Figueiredo et al. (2024) opine on the importance of data security. This is also supported by Akinradewo et al. (2021), who confirm that Blockchain can secure substantial amounts of data and support various types of transactions. Shojaei (2019) argues that, since data is encrypted, it is highly secure.

2.6.4. Efficiency and Smart Contracts

Delays at the ports are indicators of inefficiency. There are several reasons for inefficiencies at the Port. Hargaden et al. (2019) attest that blockchain technology promotes efficiencies. The traditional contractual process comes with many inherent problems. Philipp et al. (2019) and Mahmudnia et al. (2022) advocate that smart contracts provide a solution to the traditional contracting process.

2.7. Theoretical Framework

Two theoretical frameworks are critical to this research: the benchmarking framework and the efficiency theory. The benchmarking theory advocates comparing ports to serve as a basis for learning from one another, in this case, salient truths that can be gleaned from the Port of Rotterdam. According to Wong and Wong (2008), Benchmarking can be applied to the Port of Rotterdam because it serves as a representative of best practices, especially for continuous improvement in blockchain technology. Benchmarking is learning from others and involves leveraging their knowledge and experience to improve the organisation (Lankford, 2002). Optimal inputs that yield the desired outputs, in view of scarcity, are the bedrock of efficiency theory (Camanho et al., 2024). Efficiency is critical because the results from the Malmquist Productivity Index Data Envelopment Analysis (MPI-DEA) show the level of efficiency for the selected ports.

3. Research Methodology

This research adopts the Saunders, Lewis, and Thornhill (2019) Research Onion framework, which is classified into research philosophy, research approach, research strategy, choices, time horizon, techniques, and procedure. The positivist approach was used because the secondary data were collected from the unit of analysis, the selected ports. Positivism emerged from foundationalism and empiricism; positivists value objectivity and the testing of hypotheses (Blackwell, 2018). Deductive reasoning aligns with the numerical data obtained from port stats and is used to determine the port efficiency.

This research employs a multi-method approach, including a scoping review, to examine the application of BCT in the construction materials supply chain. Then, a Quantitative Research Approach was used, drawing on the cases of the Port of Durban and Rotterdam. For calculating efficiency, input and output parameters are required. The inputs are the number of container berths, the number of tug boats, the number of terminals, the number of cranes, the number of port employees, and the length of the quay, whilst the outputs are vessel visits and container throughput. This secondary data for 2017-2023 is sourced from the Port of Rotterdam's and Transnet Port statistics. This data set has been validated by various port information systems, as well as by artificial intelligence and blockchain technology, which provide real-time data. This data set has been confirmed and validated by another source, such as the World Bank CPPI (2023) report. The sampling technique used is purposive sampling, as the Port of Rotterdam is among the few smart ports to have implemented blockchain technology.

This research adopts the Malmquist Productivity Index (MPI) to measure efficiency over time. The Malmquist index (MI) evaluates the efficiency change over time. It is a non-parametric framework measured as the product of catch-up (or recovery) and frontier-shift (or innovation) terms, both derived from DEA technologies (Tone, 2004). Efficiency is measured by the ratio of Output to inputs.

This research uses the Malmquist Productivity Index from data envelopment analysis to evaluate port efficiency and productivity for the Port of Durban and the Port of Rotterdam from 2017 to 2023. The Port of Durban and Rotterdam are the Decision Making Units-DMUs, hence a case study approach. The following shows the importance of the inputs and outputs.

3.1. Inputs

Number of Container Terminals: This is critical as they provide the main infrastructure responsible for loading and unloading the containers full of materials (Martinez-Moya, 2025).

Number of Container Berths: The first point of arrival at the Port is the berth; this is where container terminal offloading and unloading operations begin (Jiang et al., 2024). Hence, to prevent delays, there must be more berths or a process of enhancing the flow of vessels.

Number of Cargo Handling Equipment (Cranes): This is linked to port productivity (Ningrat et al., 2024).
Number of Tugs: Tugs are important navigational tools for Vessels entering ports (Paulauskas et al., 2021).

Length of Quay: This determines the types and sizes of vessels permitted to berth, and it is crucial to port productivity (Jeong & Kim, 2024).

Port Employees: This has a positive impact on port productivity (Ayesu & Boateng, 2024).

3.2. Outputs

Container Throughput: The number of 20 Ft and 40 Ft containers offloaded or loaded on the vessel. This is very critical for port employment. (Ayesu and Boateng, 2024).

Vessel Visits: Chu et al. (2023) posit that the punctuality of vessel visits or calls is crucial for port operations.

According to Negar and Rostamy-Malkhalifeh (2017), MPI shows the regression and progression of decision-making units, such as ports, over time. The two periods are the efficiency change and the technology change. Negar and Rostamy-Malkhalifeh (2017) state that the MPI indicates that the regression and progress of a unit from one period to the next depend not only on its efficiency changes during these two periods, but also on technological changes in the population or on a boundary shift of the evaluated population in the same period. Equation 1 is the MPI formula. The Pim-Dea V.3.0 software, developed by Emrouznejad and Thanassoulis (2024), is useful for calculating productivity for the selected harbours from 2017 to 2023. The DEA model is input-oriented, and variable returns to scale are assumed.

$$M(Y_{t+1}, X_{t+1}, X_t) = \underbrace{\frac{D^t(Y_{t+1,}X_{t+1})}{D^t(Y_{t,}X_t)}}_{Efficiency\ change} \underbrace{\frac{D^t(Y_{t+1,}X_{t+1})}{D^{t+1}(Y_{t+1,}X_{t+1})} X \frac{D^t(Y_{t,}X_t)}{D^{t+1}(Y_{t,}X_t)}}_{Technology\ change}$$

Equation (1): The MPI

Source: Malmquist (1953)

Negar and Rostamy-Malkhalifeh (2017) state that when the DMU0, MPU0 is greater than 1, progress occurs in the period t+1 ratio to t.; However, if the DMU0, MPU0 is less than 1: A regression occurs in period t+1 ratio to t and when the DMU0, MPU0= 1: No progress or regression occurs in period t+1 ratio to t.

4. Results and Discussion

Three major categories are discussed in this section: the application of BCT on CMSC, the application of Blockchain Technology at the Rotterdam harbour, and the enablers of port productivity for the Durban and Rotterdam Harbours.

4.1. Application of BCT in the Construction Materials Supply Chain (CMSC)

Blockchain technology is well-suited to facilitating the construction material supply chain. Based on a literary search of over 50 articles using keywords like BCT, construction materials supply chain. The Application of Blockchain has been streamlined into four major themes, as depicted in Figure 1. These include smart contracts, track-and-trace, accelerated document flow, and authentication and validation of documentation and stakeholders. Shojaei (2019) posits that the implementation of blockchain technology in the construction industry can also lead to the use of smart contracts, which will reduce administrative burdens and improve the flow of project, material, and service delivery. Elmay et al. (2022) attest that Blockchain accelerates the inefficient shipping process by digitising ownership transfer and process documentation. Wang et al. (2021) posit that Blockchain enables simultaneous auditing and makes real-time optimisation possible for partners and

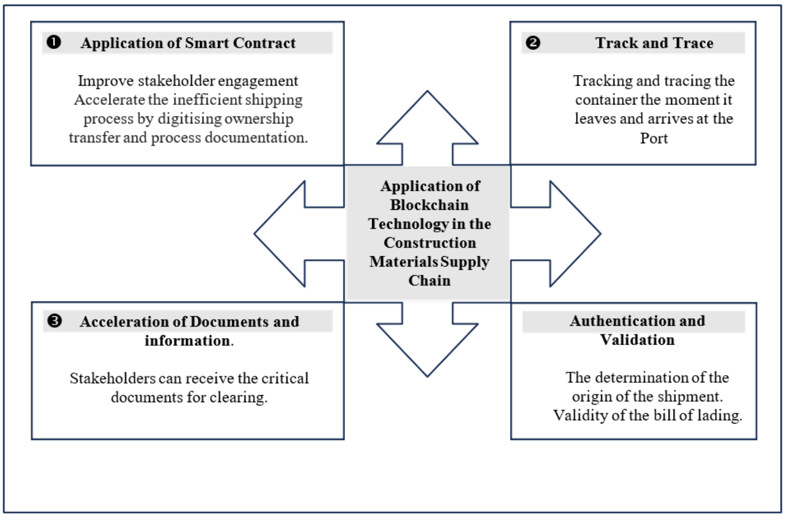

Figure 1: Application of BCT in Construction Material Supply Chain
Source: Author's, 2025

organisations. Nasih et.al. (2024) confirm the use of BCT to improve tracking and tracing services, ensuring data integrity, transparency, and traceability across supply chains.

4.2. Application of Blockchain Technology at the Port of Rotterdam.

Wang et al. (2021) posit that shared distributed digital technology in the maritime industry improves customs clearance efficiency and logistics transparency. Quay Connect was born out of the struggles experienced in importing and exporting between the Netherlands and the UK. It was developed as an independent blockchain platform to facilitate the exportation of shipments from the Netherlands to the United Kingdom (Port of Rotterdam, 2025). The benefit of this application is the automatic exchange of information with the customs authorities at ports in the United Kingdom (Farah et al., 2024). The implication is that exporters from the Netherlands can digitise and streamline the export and customs process. This results in a 30% savings on the cost of each customs clearance (Port of Rotterdam, 2025).

4.3. The enablers of port productivity for the Durban and Rotterdam Harbour

Productivity measures for ports are important for port stakeholders (Gonzalez, 2022). The port productivity of both the Port of Rotterdam and the Port of Durban is analysed from 2017 to 2023. The results of these analyses are categorised into efficiency change and technology change. The product of efficiency changes and technological progress makes up the Malmquist Productivity Index. The Pim-Dea V.3.0 software developed by Emrouznejad and Thanassoulis (2024) calculates the efficiency change for the selected ports from 2017 to 2023.

4.3.1. Efficiency Change

The efficiency change component measures how well a firm, in this case the Durban and Rotterdam harbours, uses its resources to produce a given level of output. Both the Port of Durban and Rotterdam make optimal use of their resources, as indicated by level 1. Figure 2

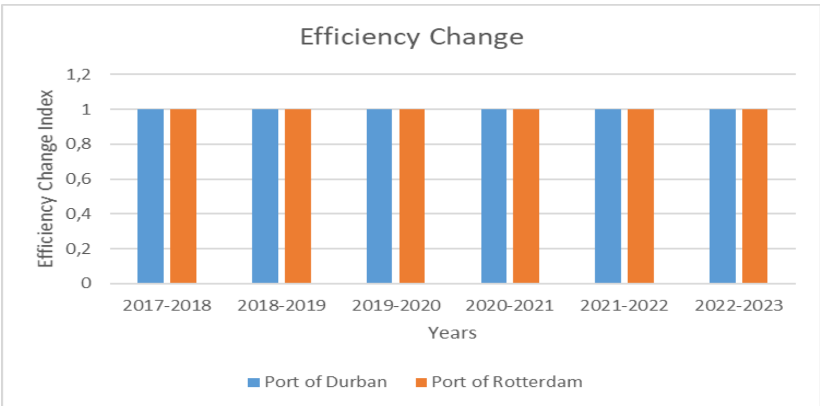

Figure 2: Efficiency Change
Source: Author's Compilation, 2024

and Table 2 show that efficiency has been consistent throughout the years examined. of productivity. This is confirmed by Van Den Bosch et al. (2011) and Osundiran and Makgopa (2025).

Table 2: Numerical DEA-MPI

Port	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023
Technology Change						
Port of Rotterdam	3,16	1	2,98	3,34	2,87	3,31
Port of Durban	1,1	0,94	0,88	1,03	0,97	0,99
Port	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023
Efficiency Change						
Port of Rotterdam	1	1	1	1	1	1
Port of Durban	1	1	1	1	1	1
Malmquist Productivity Index						
Port	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023
Port of Rotterdam	3,16	1	2,98	3,34	2,87	3,31
Port of Durban	1,1	0,94	0,88	1,03	0,97	0,99

Source: Author,2024

4.3.2. Technology Change

Technological change measures the shift in the production frontier over time. As the frontier shifts upward, more outputs can be obtained from the same level of inputs. Technology is a major driver of productivity. In Figure 3 and Table 2, there is a clear-cut demarcation of the impact of technology on port productivity for the Port of Rotterdam. The Port of Durban still has much room for improvement in the application of suitable, customised technology to improve port performance. The point of inflexion for the Port of Durban in 2018-2019 was due to operational inefficiencies (Dlamuka, 2022). Throughout the examination period, Rotterdam maintained a high level

Nevertheless, Rotterdam's higher MPI is not necessarily attributable solely to blockchain technology but to other factors, such as artificial intelligence, geographic positioning, and operational efficiencies (Fani, 2025).

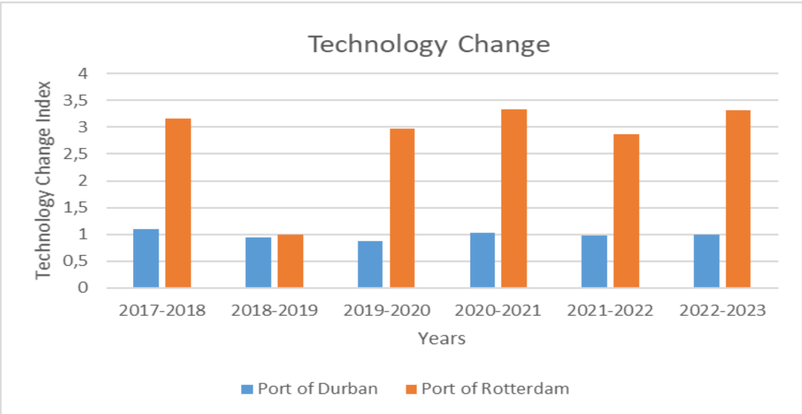

Figure 3: Technology Change
Source: Author's Compilation, 2025

4.3.3. The Malmquist Productivity Index

From Figure 4 and Table 2, the Rotterdam harbour has a greater Malmquist Productivity Index than the Port of Durban. The Technology factor plays a crucial role in the Port of Rotterdam's performance. Figure 4 shows the impact of technology on productivity at the Rotterdam port. Over the years examined except for 2018-2019. The Port of Rotterdam has improved

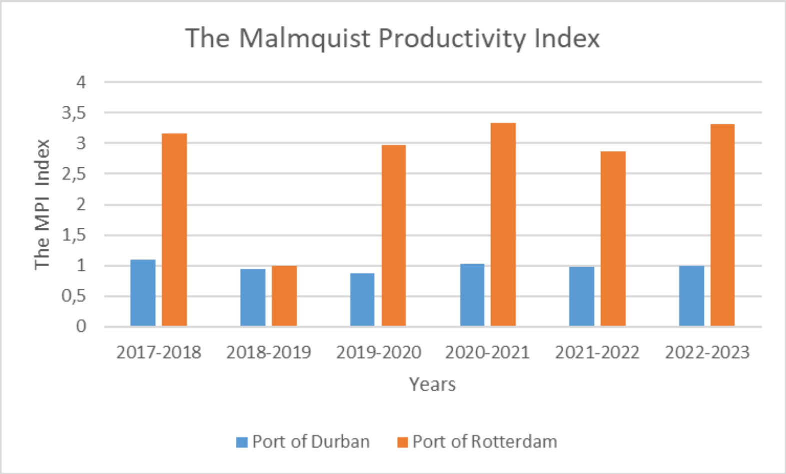

Figure 4: The Malmquist Productivity Index
Source: Author's Compilation, 2024

productivity through technology.

Table 2 shows the numerical breakdown of the results for the Ports of Durban and Rotterdam for 2017-2023. It captures the technological and efficiency changes, then presents the Malmquist Productivity Index result.

4.4. Compare the various applications of technology at the Durban and Rotterdam Harbours

This section compares the Port of Rotterdam with the Port of Durban using several parameters. Elhussieny (2025) posits that the Port of Rotterdam is ranked highly in Europe and globally. However, World Bank CPPI (2023) indicates that the Port of Durban is struggling in terms of its performance. Table 3 shows the various parameters used to compare.

5. Conclusion and Further Research

Port congestion is associated with vessels lining up along the Port's shores. Leading to delays, queuing, and extra time for the voyage and the docking of ships and cargo at the Port. This research was conducted due to the persistent delays that importers of construction materials experience at the Port of Durban. The research further used the Port of Rotterdam as a basis for comparison, as it is not only a smart port but has also used Blockchain Technology. This study identified various applications of blockchain technology to

Table 3: The Application of Technology at the Selected Ports

Parameter	Ports		Comments on the Port of Rotterdam	Comments on the Port of Durban
	Port of Rotterdam	Port of Durban		
Type of Port	Smart	Traditional	Smart because of the adoption of the latest and relevant technology.	Very traditional in its operations
Technology Type	Blockchain (Quay Connect) HAMIS- Haven Management Information System Artificial Intelligence Twin Digitalisation.	Navis Sparcs N4 Electronic Data Interchange General Cargo Operating System AVEVA Software to reduce the risk of load shedding	Partners with several Universities and Software Companies	There is a need for more stakeholder engagement.
The Role of Technology	The existing technology that is being used in Rotterdam is crucial to facilitating the construction materials supplychain.	The technology used is not adequate to mitigate the current operational risks and delays experienced at the Port of Durban.	Proven track record in handling efficiency issues.	There is need to upgrade the current technology mix to improve efficiency at the Port of Durban.

Source: Authors, 2025

facilitate the supply chain for construction materials. This lends credence to the importance of Blockchain in the areas of smart contracts, shipment tracking and tracing, accelerated document flow, and authentication and validation of documentation among stakeholders. The study demonstrated that technology can be a major driver of port productivity.

Furthermore, the enormous gap in port productivity, as shown in Figure 4, underscores the importance of innovation and technology in the Port of Rotterdam, as noted by Osundiran and Makgopa (2025). Finally, the study compares the various applications of technology at the Port of Durban and Rotterdam. The research also notes that, even though the Port of Rotterdam is more productive and digital, blockchain technology is not the only causal factor.

This research suggests that the port authority, construction companies, and other stakeholders recognise the benefits of Blockchain in facilitating the construction material supply chain. For instance, Quay Connect is the collaboration between the Port of Rotterdam, Brexit and Importers and Exporters. This customised BCT was developed to address the challenges of import-export between European nations. Particularly since BCT provides a way forward for addressing port inefficiencies, for instance, Smart contracts can activate real-time actions or transactions as soon as the predefined contractual clauses and rules are fulfilled (Phillip et al., 2019). Furthermore, the Port of Rotterdam engages its stakeholders in a way that ensures the technology used in the port is well-suited to meet the needs of the Port and its stakeholders. Therefore, this study recommends that a customised Blockchain be adopted between the construction companies and the South African Port.

The study's limitations include focusing on two sets of DMUs, omitting variables such as hinterland infrastructure, and having a short timeline. The study does not empirically test the impact of BCT in Durban, and the policy recommendation is based on analogy and literature rather than intervention evidence.

Further research can be conducted on the efficiency of ports after the adoption of Blockchain Technology in subsequent years to determine whether there is an improvement or a further decline in port efficiency.

References

Adel, K., Elhakeem, A. & Marzouk, M. (2022). Decentralising construction AI applications using blockchain technology. *Expert Systems with Applications*, *194*, p.116548.

Akinradewo, O., Aigbavboa, C., Oke, A., Mthimunye, I. (2021). Applications of Blockchain Technology in the Construction Industry. In: Markopoulos, E., Goonetilleke, R.S., Ho, A.G., Luximon, Y. (eds) Advances in Creativity, Innovation, Entrepreneurship and Communication of Design. AHFE 2021. Lecture Notes in Networks and Systems, vol 276. Springer, Cham. https://doi.org/10.1007/978-3-030-80094-9_33

Ayesu, E. K., Sakyi, D., & Baidoo, S. T. (2022). The effects of seaport efficiency on trade performance in Africa. *Maritime Policy & Management*, *51*(3), 420–441. https://doi.org/10.1080/03088839.2022.2135178

Ayesu, E.K., Boateng, K.A.B. (2024). Estimating the impact of container port throughput on employment: an analysis for African countries with seaports. *J. Shipp. trd.* **9**, 8 (2024). https://doi.org/10.1186/s41072-024-00166-z

Basheer, M., Elghaish, F., Brooks, T., Rahimian, F.P. & Park, C. (2024). Blockchain-based decentralised material management system for construction projects. Journal of Building Engineering, 82, p.108263.ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2023.108263

Blackwell, R. G. (2018). Introduction to positivism, interpretivism and critical theory. Nurse Researcher. 25. 14–20. 10.7748/nr. 2018.e1466.

Böhmecke-Schwafert, Moritz, 2024. "The role of blockchain for trade in global value chains: A systematic literature review and guidance for future research," Telecommunications Policy, Elsevier, vol. 48(9).

Camanho Ana Santos, Maria Conceicao Silva, Fabio Sartori Piran, Daniel Pacheco Lacerda, (2024). A literature review of economic efficiency assessments using Data Envelopment Analysis, European Journal of Operational Research, Volume 315, Issue 1, 2024, Pages 1-18, ISSN 0377-2217, https://doi.org/10.1016/j.ejor.2023.07.027.

Chu, Z., Yan, R., & Wang, S. (2023). Evaluation and prediction of punctuality of vessel arrival at Port: a case study of Hong Kong. *Maritime Policy & Management*, *51*(6), 1096–1124. https://doi.org/10.1080/03088839.2023.2217168

Danladi, C., Tuck, S., Tziogkidis, P. *et al. (2024)*. Efficiency analysis and benchmarking of container ports operating in lower-middle-income countries: a DEA approach. *J. Shipp. trd.* **9**, 7 (2024). https://doi.org/10.1186/s41072-024-00163-2

Dlamuka M.T. (2022). Key performance indicators for container ports: A case of Weighted Efficiency Gains from Operations (WEGO) in South Africa. Available online: https://share.google/y99kaNnzqksVfbo5T Accessed 18 Dec 2025.

Elhussieny, M. (2025). Smart green ports: a sustainable solution for the maritime industry in a changing climate. *Multidisciplinary Adaptive Climate Insights,* *2*(1), 1–30. doi:https://dx.doi.org/10.21622/MACI.2025.02.1.1162

Elmay, F.K., Salah, R., Jayaraman, & I. A. Omar (2022). "Using NFTs and Blockchain for Traceability and Auctioning of Shipping Containers and Cargo in Maritime Industry," in *IEEE Access*, vol. 10, pp. 124507–124522, 2022, doi: 10.1109/ACCESS.2022.3225000

Fani, V. (2025). Assessing the adoption of artificial intelligence in the maritime transport industry: an empirical exploration in the Port of Rotterdam: V. Fani. *Maritime Economics & Logistics*, pp.1–15.

Farah Mohamed Ben, Yussuf Ahmed, Haithem Mahmoud, Syed Attique Shah, M. Omar Al-kadri, Sandy Taramonli, Xavier Bellekens, Raouf Abozariba, Moad Idrissi, Adel Aneiba (2024). A survey on blockchain technology in the maritime industry: Challenges and future perspective Future Generation Computer Systems, Volume 157, 2024, Pages 618–637, ISSN 0167-739X, https://doi.org/10.1016/j.future.2024.03.046.

Figueiredo, K., Hammad, A.W., Pierott, R., Tam, V.W. & Haddad, A. (2024). Integrating digital twin and Blockchain for dynamic building life cycle sustainability assessment. *Journal of Building Engineering*, *97*, p.111018.

Gonzalez, M. (2022). Port productivity: benchmarking analysis of strategic ports. International Journal of Productivity and Performance Management. 73. 10.1108/IJPPM-09-2022-0453.

Griessel, J. (2024). 'Interrupted supply chain infrastructure: Global supply risk or opportunity?', *Bizcommunity.com*, 15 Feb, NA, available: https://link.gale.com/apps/doc/A782670676/HRCA?u=anon~ad56ea19&sid=googleScholar&xid=f6f95a3d [accessed 13 Nov 2024].

Guan, P., Wood, L.C., Wang, J.X. & Duong, L.N. (2024). Blockchain adoption in the port industry: a systematic literature review. *Cogent Business & Management*, *11*(1), p.2431650. doi: 10.1080/23311975.2024.2431650

Ghamari, H.; Hamidreza Abbasianjahromi, Seyed Mohammad Mirhosseini (2024). Providing a framework to optimise the sustainable construction material supply chain with the possibility of horizontal transfers, Sustainable Futures, Volume 8, 2024, 100328, ISSN 2666-1888, https://doi.org/10.1016/j.sftr.2024.100328.

Hargaden, V., Papakostas, N., Newell, A., Khavia, A. & Scanlon, A. (2019). June. The role of blockchain technologies in construction engineering project management. In *2019, the IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1–6). IEEE.

International Trade Administration (2024) 'Port and Marine" Available from https://www.trade.gov/country-commercial-guides/south-africa-ports-and-marine Accessed online 13 Dec 2024.

Jeong, B., Kim, C.Y.(2024). Containership size and quay crane productivity: empirical evidence from Busan New Port. *Marit Econ Logist* (2024). https://doi.org/10.1057/s41278-024-00286-0

Jiang, M., Ma, F., Zhang, Y., Lv, S., Pei, Z., & Wu, G. (2024). Collaborative Scheduling Optimisation of Container Port Berths and Cranes under a Low-Carbon Environment. *Sustainability*, *16*(7), 2985. https://doi.org/10.3390/su16072985

Kao, C. (2023). Output–Input Ratio Efficiency Measures. In: Network Data Envelopment Analysis. International Series in Operations Research & Management Science, vol 340. Springer, Cham. https://doi.org/10.1007/978-3-031-27593-7_2

Khalifa, F. & Marzouk, M. (2025). Integrated blockchain and Digital Twin framework for sustainable building energy management. Journal of Industrial Information Integration, 43, p.100747.ISSN 2452-414X, https://doi.org/10.1016/j.jii.2024.100747

Kim, K., Lee, G., & Kim, S. A. (2020). Study on the Application of Blockchain Technology in the Construction Industry. *KSCE J Civ Eng* **24**, 2561–2571 (2020). https://doi.org/10.1007/s12205-020-0188-x

Kiu, M. S., Chia, F. C., & Wong, P. F. (2020). Exploring the potentials of blockchain application in construction industry: a systematic review. *International Journal of Construction Management*, *22*(15), 2931–2940. https://doi.org/10.1080/15623599.2020.1833436

Lankford, W. M. (2002). "Benchmarking: Understanding the Basics," *The Coastal Business Journal*: Vol. 1: No. 1, Article 8. Available at: https://digitalcommons.coastal.edu/cbj/vol1/iss1/8 Accessed 26 Aug, 2024.

Leah P (2024). 'Construction Materials Shortages in South Africa', *Kwa Zulu Natal Master Builder Newsletter*, Available online: https://www.masterbuilders.co.za/news/674054/Construction- Material-Shortages-in-South-Africa.html Accessed 13 Dec 2024.

Li, J., Han, D., Weng, T.H., Wu, H., Li, K.C. & Castiglione, A. (2025). A secure data storage and sharing scheme for port supply chain based on Blockchain and dynamic searchable encryption. Computer Standards & Interfaces, 91, p.103887.

Liu, J., Zhang, H., & Zhen, L. (2021). Blockchain technology in maritime supply chains: applications, architecture and challenges. *International Journal of Production Research*, *61*(11), 3547–3563. https://doi.org/10.1080/00207543.2021.1930239

Mahmudnia, D., Arashpour, M. and Yang, R., (2022). Blockchain in construction management: Applications, advantages and limitations. *Automation in construction*, *140*, p.104379.

Malmquist, S. (1953). Index Numbers and Indifference Surfaces. *Trabjos de Estatistica*, Vol.4(2), pp.209-242

Martinez-Moya, J., Vanelslander, T., Feo-Valero, M. & Sala-Garrido, R. (2025). "Evaluating container terminal competitiveness in the Hamburg – Le Havre range", Maritime Business Review. ahead-of-print. https://doi.org/10.1108/MABR-04-2024-0037

Mazibuko, D., Mutombo, Kana, & Kuroshi, Lawrence. (2024). An evaluation of the relationship between ship turnaround time and key port performance indicators: a case study of a Southern African port. WMU Journal of Maritime Affairs. 23. 10.1007/s13437-024-00330-z.

Meersman, H., Van de Voorde, E. and Vanelslander, T. (2012). "Port Congestion and Implications to Maritime Logistics", Song, D.-W. and Panayides, P.M. (Ed.), Maritime Logistics, Emerald Group Publishing Limited, Leeds, pp. 49-68. https://doi.org/10.1108/9781780523415-004

Monrat, A.A. O. Schelén & K. Andersson (2019). "A Survey of Blockchain From the Perspectives of Applications, Challenges, and Opportunities," in IEEE Access, vol. 7,

Mthembu, S.E., Chasomeris, M.G. A systems approach to developing a port community system for South Africa. J. Shipp. trd. 7, 26 (2022). https://doi.org/10.1186/s41072-022-00128-3

Negar D, Mohsen Rostamy-Malkhalifeh (2017). Malmquist Productivity Index In Ratio Data Envelopment Analysis Journal of Data Envelopment Analysis and Decision Science 2017 No. 1 (2017) 7-13Available online at www.ispacs.com/dea Volume 2017, Issue 1, Year 2017 Article ID: dea-00143, 7 pages doi:10.5899/2017/dea-

Nemakhavhani Rotondwa & Thabo Khafiso. (2024). Time overruns in South African construction projects: Unveiling challenges and solutions from a contractor's viewpoint. 282–290. 10.1201/9781003483519-31.

Nikjow, M.A.; Liang, L.; Qi, X.; Sepasgozar, S.M.E.; Chileshe, N. (2021) Triggers of Delays in International Projects Using Engineering Procurement and Construction Delivery Methods in the Belt and Road Initiative: Case Study of a High-Speed Railway Project. *Sustainability* **2021**, *13*, 9503. https://doi.org/10.3390/su13179503

Ningrat, A., Tahir, A., Rusnaedi, R., & Muslihati. (2024). Optimising Container Crane Performance: Enhancing Loading and Unloading Productivity at PT. Kaltim Kariangau Terminal. *Indonesian Journal of Maritime Technology*, *2*(2). https://doi.org/10.35718/ismatech.v2i2.1264

Obasi C & S., Oyakegha & M., Okuoyibo. (2024). Port Logistics and Supply Chain Management: An Empirical Review. African Journal of Economics and Sustainable Development. 7. 82–91. 10.52589/AJESD-CB4SA99C.

Okanlawon, T.T., Oyewobi, L.O. & Jimoh, R.A. (2025). Effect of blockchain technology adoption on construction supply chain: a structural equation modelling (SEM) approach. *Journal of Facilities Management*, *23*(3), pp.407–428.

Osundiran, A.O. & Makgopa, T. (2025). An Examination of the Impact of Artificial Intelligence on Maritime Port Efficiency and Businesses. In *Diversity, AI, and Sustainability for Financial Growth* (pp. 255–288). IGI Global Scientific Publishing.

Pallis, A., Theo Notteboom, & Jean-Paul Rodrigue (2022). Port Economics, Management and Policy, New York: Routledge, 690 pages / 218 illustrations. ISBN 9780367331559. Available from doi.org/10.4324/9780429318184 [Accessed 18th December 2023]

Paulauskas, V., Simutis, M., Plačiene, B., Barzdžiukas, R., Jonkus, M., & Paulauskas, D. (2021). The Influence of Port Tugs on Navigational Safety in the Port. *Journal of Marine Science and Engineering*, *9*(3), 342. https://doi.org/10.3390/jmse9030342

Philipp, R., Prause, G. & Gerlitz, L. (2019). Blockchain and smart contracts for entrepreneurial collaboration in maritime supply chains. *Transport and Telecommunication Journal*, *20*(4), pp.365-378

Port of Rotterdam 'AI' (2024). Available online https://www.portofrotterdam.com/en/port-future/innovation/artificial-intelligence-port [Accessed 25 Aug 2024]

Port of Rotterdam 'Quay Connect' (2021). Available online https://www.portofrotterdam.com/en/news-and-press-releases/digital-quay-connect-service-makes-export-to-the-uk-cheaper-and-more [Accessed 17 Dec 2025]

Port of Rotterdam (2025) successful digitalisation process. Available online https://publications.portofrotterdam.com/digital-report/successful-digitalisation-of-customs-processes [Accessed 17 Dec 2025]

Putri, S & Firmansyah,. (2020). The Efficiency of Steel Material in Building Construction. IOP Conference Series: Materials Science and Engineering. 879. 012148. 10.1088/1757-899X/879/1/012148.

San, K.M., Choy, C.F. & Fung, W.P. (2019). June. The potentials and impacts of blockchain technology in construction industry: A literature review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 495, p. 012005). IOP Publishing.

Saunders, M.N.K., Lewis, P. & Thornhill, A. (2019). Research Methods for Business Students. 8th Edition, Pearson, New York.

Shojaei, Alireza. (2019). Exploring Applications of Blockchain Technology in The Construction Industry. Proceedings of International Structural Engineering and Construction. 6. 10.14455/ISEC.res.2019.78.

Soni, M. S. M., & Smallwood, J. J. (2023). Perceptions of Corruption in the South African Construction Industry. *International Journal of Construction Education and Research*, *20*(1), 43–64. https://doi.org/10.1080/15578771.2023.2179138.

South African Iron and Steel Institute (2025). Available online: https://www.saisi.org/imports-primary-products/ Accessed 16 Dec 2025.

Suárez-Alemán, et al.,. (2016). When it comes to Container Port Efficiency, Are All Developing Regions Equal? *Transportation Research* Part A 86, pp.56–77. Available at: http://dx.doi.org/10.1016/j.tra.2016.01.018 0965-8564/_ 2016 [Accessed 31 10 17].

Tone Kaoru (2004). Malmquist Productivity Index Handbook on Data Envelopment Analysis, 2004, Volume 71 ISBN: 978-1-4020-7797-5

Tovar Beatriz & Wall Alan, (2024). Persistent and transient inefficiency in ports: An application to Spanish port authorities, Research in Transportation Business & Management, Volume 54, 2024, 101124, ISSN 2210-5395, https://doi.org/10.1016/j.rtbm.2024.101124

Transnet (2024). Transnet Port Terminals. Available from https://www.transnet.net/Divisions/Pages/TPT.aspx, accessed 26 Jul 2024.

UNCTAD (2023). Review of Maritime Transport: Towards a Green and Just Transition. https://unctad.org/publication/review-maritime-transport-2023

United States Department of Agriculture (2024) Foreign Agriculture Service. Report Name: Port Challenges Cause Shio and Export Opportunities to Pass South Africa by https://www.fas.usda.gov/data/south-africa-port-challenges-cause-ships-and-export-opportunities-pass-south-africa#:~:text=The%20South%20African%20ports%20have,through%20a%20focused%20turnaround%20plan.

Van Den Bosch, F.A., Hollen, R., Volberda, H.W. and Baaij, M.G., (2011). The strategic value of the Port of Rotterdam for the international competitiveness of the Netherlands: A first exploration. *Erasmus University Rotterdam, Rotterdam School of Management (RSM). Rotterdam: Port of Rotterdam*.

Wang, J., Liu, J., Wang, F., & Yue, X. (2021). Blockchain technology for port logistics capability: Exclusive or sharing. *Transportation Research Part B: Methodological*, *149*, pp.347–392.

Waqar, A., Qureshi, A.H., Othman, I., Saad, N. & Azab, M. (2024). Exploration of challenges to the deployment of Blockchain in small construction projects. *Ain Shams Engineering Journal*, *15*(2), p.102362.

Wong, W.P. and Wong, K.Y. (2008). A review of benchmarking of supply chain performance measures. Benchmarking Int. J., 15 (1) (2008), pp. 25–52, 10.1108/14635770810854335Wong, W. P. (2008). A review on benchmarking of supply chain performance measures, 15 (1), 25–51.

World Bank The Container Port Performance Index (WB-CPPI) (2023): A Comparable Assessment of Performance based on Vessel Time in Port (English). Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/099060324114539683

World Shipping Council (2022). Port Ranking. Available online https://www.worldshipping.org/top-50-ports Accessed 3 Sept 2024.

Xu, X., Yang, Y.(2024). Correction to: Analysis of logistics port transportation efficiency evaluation based on blockchain technology. *Ann Oper Res* **332**, 1209 (2024). https://doi.org/10.1007/s10479-021-04477-3

Yen Barbara T.H. & Corinne Mulley (2023). Introduction to the themed volume on transport efficiency, Research in Transportation Business & Management, Volume 46, 2023, 100949, ISSN 2210-5395, https://doi.org/10.1016/j.rtbm.2023.100949.

Žiga Turk, Robert Klinc (2017). Potentials of Blockchain Technology for Construction Management, Procedia Engineering, Volume 196, 2017, Pages 638–645, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2017.08.052.

Appendix 1

Table1: Significance of Blockchain Technology in Construction

S/N	Authors	Significance of Blockchain Technology in Construction
1	Kim, K., Lee, G. & Kim, S. A. (2020)	Reduces and Manages Project Cost; enhances the process of change Management; Assists in Contract Bidding and Formation, and fosters procurement evaluation.
2	Žiga Turk, Robert Klinc (2017)	When building information modelling (BIM) is used, Blockchain can complement by managing and assigning roles and responsibilities.
3	Shojaei, Alireza. (2019).	Data is encrypted, hence secured.
4	Philipp, et al., (2019)	Smart Contracts
5	San et al., (2019)	The construction industry should adopt blockchain technology because other technologies used across various project life-cycle stages have limitations.
6	Mahmudnia, D., Arashpour, M. and Yang, R., (2022)	Solve problems related to traditional contract forms.
7	Adel et al., (2022)	BCT secures access control for electronic records and the IT system
8	Elmay, Salah, Yaqoob, Jayaraman, Battah, & Maleh, (2022.)	The application of blockchain technology guarantees the full traceability of containers and goods in the Port.
9	Rahimi et al.,(2020)	Blockchain provides an authentication mechanism that enables secure communication for a wireless communications-assisted UAV sensing system for maritime IoT critical applications, by deploying a private Blockchain network connected to a fusion centre (FC) in the terrestrial area.
10	Nasih, et.al.,(2024).	The use of BCT improves tracking and tracing services, ensuring data integrity, transparency, and traceability across supply chains.
11	Xu, Xu & Yang, Yanbin. (2024).	Aids in improving visibility across the global supply chains.
12	Zhang & Zhang (2025).	BCT stands as an unconventional strategy
13	Hargaden et al., (2019)	Promotes the efficiency of processes
14	Kiu et al., (2020)	Blockchain technology can tackle the issue of loose collaboration among stakeholders in the construction industry.
15	Akinradewo et al. (2021)	The ability of blockchain technologies to record, enable and secure large amounts and types of transactions
16	Okanlawon et al. (2025).	Improve the construction process.
17	Figueiredo et al., (2024)	Blockchain ensures data security, integrity, and transparency.
18	Khalifa and Marzouk (2025)	Integration of Blockchain technology with others, like Digital Twin technologies
19	Waqar et al. (2024).	Enhances the sustainability of projects
20	Basheer, et al. (2024)	Applicable for integrating systems to manage construction materials and inventory to enhance the traceability and transparency of shared supply chain material information.

Source: Compiled by Authors, 2025

JCBM (2025) 8(S1) 62-71

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Risk Mitigation Strategies in Financing Renewable Energy Projects in Sub-Saharan Africa

Sam Wamuziri

College of Engineering, University of Buraimi, Oman

Received 07 October 2025; received in revised form 19 December 2025, 25 December 2025; accepted 27 December 2025
https://doi.org/10.15641/jcbm.8.S1.1929

Abstract

There is an acute electricity shortage in Sub-Saharan Africa (SSA), and electricity blackouts are common. Climate change and carbon dioxide gas emissions from conventional power-generating systems are also of great concern. Africa has vast renewable energy resources, including hydropower, solar, wind, biomass and geothermal, which are relatively unexploited. However, there is currently a knowledge gap on how renewable energy projects can be derisked to increase the flow of international private capital into them. Based on a literature review, this study aims to identify the risk factors that hinder investment in renewable energy development in SSA. The review finds that barriers to renewable energy development include fragmented electricity markets, utilities with poor balance sheets and low credit ratings, high energy transmission losses, political risks, high initial capital costs, poorly directed subsidies, insufficiently developed money markets, and a poor regulatory framework. Efficient risk mitigation strategies are proposed. The study also finds that the global utility-scale levelized costs of electricity from renewable energy resources compare favourably with those of conventional sources. Countries in SSA need to draw up a clear policy framework with legally binding targets for the contribution of renewable energy to the energy supply portfolio. In addition, subsidies currently enjoyed by conventional energy generators need to be restructured to target low-income groups. SSA countries should identify pipelines of suitable renewable energy projects, complete feasibility studies and invite potential developers. Risks faced by international investors in renewable energy projects, including political, commercial and financial risks, are insurable. SSA faces a large infrastructure financing gap. Closing this financing gap requires building efficient local capital markets to mobilise domestic savings, reduce the costs of capital for renewable energy projects, and reduce reliance on foreign debt. An important consequence of this work is that it is possible to accelerate the development of innovative financing solutions to ramp up investment and deliver clean energy for all.

Keywords: Finance, Renewable Energy Projects, Risk Management

1. Introduction

The United Nations Paris Agreement seeks to limit global warming to well below 2 degrees Celsius compared to pre-industrial levels. Achieving this goal requires all countries to take action to reduce greenhouse gas emissions (GHG). In Sub-Saharan Africa (SSA), there is also emphasis on climate-related capacity building to enable these countries to address these challenges. Since the Paris Agreement came into force, there is now a whole range of low-carbon technology solutions and new markets, particularly in the energy and transportation sectors. Zero-carbon solutions are now competitive with traditional technologies in many sectors. Renewable energy technologies have reached sufficient maturity and constitute sound investment opportunities that enable nations to reduce global warming. Africa's per capita greenhouse gas emissions are much lower than those of developed countries. However, African countries are more likely to be disproportionately affected by climate change (Agyekum et al., 2021). The United Nations Sustainable Development Goal 7 calls for universal access to modern energy services for all by 2030.

Furthermore, Agenda 2063 of the African Union seeks

[1] Corresponding Author
Email address: sam@uob.edu.om

to create a prosperous Africa with renewable energy development as one of the priority areas (African Union, 2015). At present, 789 million people worldwide lack access to electricity. Of these 648 million (or 69%) live in Sub-Saharan Africa. Over 900 million people in Sub-Saharan Africa lack access to clean cooking (Ireri and Shirley, 2021). Most families rely on charcoal for cooking. This leads to land degradation, indoor pollution and respiratory diseases. Forty per cent of the population in Sub-Saharan Africa lives on less than USD 1.90 per day, which approximates to 433 million people. Excluding South Africa, Africa's energy consumption per capita is 180 kWh annually, compared to 6,500 kWh in the EU and 11,500 kWh in the USA.

It is estimated that Africa needs an annual capital investment of USD 100 billion in the energy sector until 2040 (KfW Development Bank, 2020). Africa has seen lower investment in the energy sector than other parts of the world due to higher perceived risks for international investors (Bashir et al., 2024). Meeting this financing challenge requires contributions from all possible sources. This paper provides an overview of the renewable energy resources in Sub-Saharan Africa. It outlines the barriers and challenges of financing renewable energy expansion in Sub-Saharan Africa, followed by a policy framework that can help to de-risk renewable energy projects and scale up investment.

2. Research Method

The overall aim of the study is to identify the factors that hinder public and private sector investment in renewable energy development in SSA. Furthermore, the study aims to develop effective intervention strategies to improve energy access. The study seeks to highlight the options available for countries in SSA to improve the economic climate to attract investment into renewable energy projects. Eight research questions guide the study, namely:

1. What is the overall economic case for renewable energy in the context of SSA?

2. What are the current attitudes of the multitude of actors in SSA, including policy makers, homeowners, industry, market operators and investors, towards renewable energy development?

3. What are the biggest challenges to scaling up renewable energy investment in SSA?

4. What are the most challenging risks and uncertainties faced by investors and developers for renewable energy investments?

5. To what extent can financial derivatives be used to mitigate risks faced by investors?

6. What lessons can we draw from countries that have successfully upscaled investment in renewable energy?

7. What package of policies and incentives could make a significant impact and breakthrough to stimulate widespread adoption and investment in renewable energy in SSA?

8. How can the infrastructure financing gap in SSA be closed?

This paper reports preliminary findings from the literature. A structured and focused narrative review was undertaken, starting with the identification of peer-reviewed journals, conference papers, books, theses, dissertations, and academic reports. The literature was identified through electronic databases, including Google Scholar, Scopus, ScienceDirect, and ProQuest. The search terms used were finance, Sub-Saharan Africa, and renewable energy. The search terms were combined with the terms challenges, barriers, and potential solutions to narrow down and identify relevant academic literature. Non-academic literature, such as social media reports, newspaper articles, and unpublished reports, was excluded from the study. Other non-scholarly literature, such as blogs, wikis, tweets or other social media content, was also excluded.

3. Renewable Energy Resources in Africa

Africa has vast untapped renewable energy resources. This includes solar, geothermal, hydropower, biomass, and wind. The share of renewable energy in power generation in Sub-Saharan Africa was 29% in 2019. This is comprised of 24% hydropower and 5% other renewable energy sources. Fossil fuels account for 71% of Africa's power supply (International Renewable Energy Agency and African Development Bank, 2022). Therefore, the role played by non-hydro renewable energy resources in electricity supply in Africa has been at best marginal.

3.1. Solar Energy

Africa, as a region, has excellent solar energy potential. It is estimated that many parts of Africa receive a daily solar radiation of 4-6 kWh/m^2. Solar power can also be deployed in a decentralised manner, even in rural and remote areas of Africa. The two technologies currently employed for solar energy are solar PV and concentrated solar power (CSP). Over 95% of solar energy that is currently generated utilises solar PV technology. Only 5% of the power is based on CSP. The potential for solar PV technology is widely distributed across Africa. The potential for CSP is mainly in desert areas, as dry air is required (Komendantova et al., 2012).

If African countries could develop the right policies, the learning curve and associated cost reductions could make solar energy a pivotal part of their energy supply. The only challenge solar PV energy supply faces, particularly in off-grid solutions, is the high cost of batteries. In desert areas of North Africa, solar PV and CSP systems could play a bigger role in water desalination because the intermittency of energy supply is not an issue. Solar energy in Africa has great potential and a significant positive impact across all dimensions of sustainability, including social, economic, technical, and environmental (Maqbool and Akubo, 2022).

3.2. Wind Energy

The potential for wind energy in Africa is enormous. In terms of distribution, wind energy resources are mainly found in coastal areas of Northern, Eastern, and Southern Africa. In these areas, wind is the cheapest form of energy when hydropower is unavailable. One of the most significant challenges in developing wind power in Africa is the operation and maintenance of wind turbines. There is a lack of technical expertise and sufficient financial resources to ensure regular maintenance. By their nature, wind turbines require higher maintenance than other forms of renewable energy generation.

The countries with the greatest potential for wind power generation in Africa include Chad, Cape Verde, Sudan, Kenya, Madagascar, and Mauritania. Countries with the most considerable installed wind power at present include Egypt, Morocco, Tunisia and South Africa. Wind energy development in Africa faces technical, economic, competition, and policy challenges. Provided suitable policies are developed, wind power in Africa can transition from a small-scale industry to large-scale commercial developments (Boadu and Otoo, 2024).

3.3. Geothermal Energy

Geothermal energy originates from the Earth's volcanic activity. Underground temperatures generally increase with increasing depth at a rate of 30 degrees centigrade per kilometre. The advantages of geothermal energy are that electricity production is continuous and can therefore serve as a baseload technology. It is reliable, cost-effective and renewable. Africa's geothermal resources are most significant in the East African Rift Valley. The Western Rift Valley extends from Uganda to Mozambique, and the Eastern Rift Valley, where volcanic activity is most intense, extends from Ethiopia to Kenya, where fluid temperatures above 200 degrees centigrade can be found. In this region, the direct use of steam to produce electricity is possible. Only Kenya and Ethiopia have made some efforts to exploit geothermal energy. In Kenya, one IPP has been constructed with a capacity of 250 MW (Oluoch et al., 2020). More geothermal plants are planned, and by 2050, Kenya expects to generate 5,000 MW of electricity from geothermal energy (Olando et al, 2024).

The total technical potential of geothermal energy in Africa is 105 TWh/year, all located in East Africa (International Renewable Energy Agency, 2020). The development of geothermal energy in Africa will depend not only on sufficient heat resources but also on adequate financing (Moore et al., 2025).

3.4. Biomass

Biomass is an important source of energy in Africa. Charcoal, a biofuel, is widely used for cooking and heating in many parts of Africa. It is easier to store; it has a high energy content and low levels of smoke emissions. It is the primary source of fuel for the urban and rural poor. Charcoal production is a significant source of employment, but it can destroy trees and forests unless fast-growing varieties are used. Bioenergy is also an important renewable energy source, derived from wood pulp residues and sugar cane bagasse. Bagasse accounts for the bulk of bioenergy installed capacity in Africa.

The technical potential of bioenergy in Africa is currently estimated at 2,374 TWh/year, although the current electricity generation of biomass power projects in Africa is negligible (Namaswa et al, 2022). This potential is substantial, particularly in Central Africa, and represents the opportunity to provide a renewable electricity supply. The principal attractions are the low bioenergy feedstock costs compared to other parts of the world. However, the availability of sufficient feedstock to make electricity production attractive is a challenge, given that large-scale farming in Africa is rare.

4. Hydropower Potential in Sub-Saharan Africa

Africa has a huge hydropower potential, and estimates suggest that only 10% to 20% of it has been developed. Most countries in Eastern and Southern Africa depend heavily on hydropower. For example, the share of hydropower is Ethiopia (90%), the Democratic Republic of Congo (95%), Zambia (85%) and Uganda (83%). It is small in other countries such as South Africa, Zimbabwe and Mauritius, where electric power is generated mainly from thermal energy, including coal (International Renewable Energy Agency, 2021). Hydropower is a clean and renewable, emissions-free electricity-generating technology. However, hydropower plants are capital-intensive. The silting of dams over time and during droughts can reduce available head and power generation.

Hydropower projects are divided into two categories, namely: large hydro (greater than 10 MW) and small hydro (Less than 10 MW). The typical cost structure of developing a hydro power plant includes hydro-technical construction (60%), turbines (25%), electrical equipment (10%), buildings (5%), and exploration and other costs (0.5%). Africa has the potential to generate

350,000 MW of electricity from hydropower alone (Climate Analytics, 2022).

Hydropower will be an essential contributor to Africa's future energy mix. It can be used to provide a base load and to smooth out the intermittency of other renewable energy sources. The main reason for the current low level of hydropower development is access to finance. The perceived level of risk for international investors has also driven low investment levels. The other reason is that tariffs in many countries are political decisions and do not reflect the market costs of generating, transmitting, and distributing electricity. There is an urgent need in many countries to develop transparent, fair regulations and a policy framework. An energy pricing system that reflects electricity production costs is necessary to attract private-sector investment. As the technology for hydropower production is proven, raising private-sector investment in hydropower should be straightforward, provided appropriate risk-mitigation strategies are implemented.

5. Unit Costs of Renewable Energy Generation

The falling costs of renewable energy generation over recent years offer an opportunity to unlock this potential. Compared to other power generation sources, such as nuclear or fossil fuels, the construction of solar and wind power generation has short construction lead times, and so implementing these technologies could fast-track access to the electricity supply. The estimated global levelized cost in USD/ KWh of utility-scale electricity power generation from various renewable energy sources is as follows: Bioenergy (0.067), Geothermal (0.068), Hydropower (0.048), Solar PV (0.048), Concentrating Solar Power (0.114), Onshore Wind (0.033), Offshore Wind (0.075) (International Renewable Energy Agency, 2021).

This data indicates that the financial and economic viability of renewable energy generation is now well established and competitive with conventional technologies. Given the low costs of hydropower, solar PV and onshore wind technologies, African governments must focus on removing institutional barriers and developing a pipeline of renewable energy projects to make progress. The costs of renewable energy generation depend on the technology employed. The quality and availability of energy resources, project details, and the specific site also influence power generation costs. The costs of project implementation in Africa are also higher than in other countries because of additional transportation costs and import duties. Economies of scale are important in power projects. Large projects are generally cheaper per kWh. There are also skills gaps for operations and maintenance. In the next section, a brief review of infrastructure financing in developed and developing countries is provided, along with the economic rationale.

6. Review of Project Finance for Infrastructure

The early 1980s saw the revival of using project finance to fund infrastructure investments in telecommunications and power generation in developing countries. Brealey et al. (1996) argue that equity investment by shareholders in such projects, together with high leverage and the complex web of contractual arrangements, reduces agency problems in the design, construction, operation, and maintenance of large infrastructure projects. Additionally, Kensinger and Martin (1988) note that project finance, which is centuries older than shares or bonds, gained widespread use in the 1980s for financing the construction of industrial developments, factories, oil and gas exploration projects, power generation, and research and development, and highlighted its potential to catalyse change in the governance of business activities.

Esty (2003) provides detailed case histories on the structuring, valuation, risk management, and project financing of a wide range of infrastructure investments in developed and developing countries, including Islamic finance. Meanwhile, Shah and Thakor (1987) provide the economic rationale for project finance. In their theoretical analysis of the capital structure, they show that riskier firms acquire more debt, pay higher interest rates, but have higher equilibrium values. They argue that project finance is optimal when there is asymmetric information between insiders within the firm and external market participants. In other words, the market value of the riskiest projects is maximised with project financing.

The United Kingdom government launched the Private Finance Initiative (PFI) in 1992 to use private-sector funding to design, build, operate, and manage essential public infrastructure projects such as schools, roads, hospitals, and prisons. The rationale for this policy was to introduce market discipline in the development and provision of infrastructure services and to transfer risk to the private sector. The policy, however, faced criticism due to the complexity of the procurement processes, procedures, and costs.

The PFI was rebranded as the Public-Private Partnership (PPP) programme by the Labour government in 1997, which expanded the programme's scope and the number and value of projects commissioned under it. The refurbishment and modernisation of the London Underground was one of the projects procured under the PPP program. This was one of the most high-profile projects in Britain at the time, and the significant challenges it faced, leading to a buyout by the central government, highlighted that PPPs are not a panacea for infrastructure financing challenges (Glaister, 2025).

Grout (1997) provides an analysis of the economics of the PFI programme, concluding that although this approach incentivises construction contractors to limit time and cost overruns, it does not limit the public sector borrowing requirement in the long run.

In their analysis of the strategic factors driving innovation in infrastructure finance, Badu et al. (2013) note that the infrastructure deficit in developing countries is inextricably linked to a lack of funding. Additionally, Estache (2010) shows that the private sector has limits as a source of financing for infrastructure projects in the third world. Therefore, public sector support is needed if infrastructure services are to be offered at affordable, commensurate prices with consumers' ability to pay in developing countries.

A brief review of the barriers to renewable energy development in SSA and potential solutions is discussed next.

7. Barriers to Renewable Energy Development in Africa and Potential Solutions

7.1. Structure of Electricity Markets in Sub-Saharan Africa

The economic case for developing and expanding renewable energy in Africa is strong. Feasibility studies need to be conducted for specific locations, projects and technologies. For rural populations in Africa without access to electricity, grid extension is encouraged. However, electricity markets in many African countries are still relatively small, so utility companies do not benefit from economies of scale. A significant proportion of people, particularly in rural areas in Africa, also live subsistence livelihoods. Thus, extending electricity to rural areas requires governments to address affordability concerns. This is part of the reason many developing-country governments in Africa have favoured rural electrification strategies over renewable energy development. Thus, providing access to electricity must be addressed in tandem with poverty eradication and other programs that seek to raise household incomes in rural areas (Sachs, 2015).

The other challenge in electricity supply, particularly in SSA, is the large gap between electricity demand and the available generating capacity. The overall state of the generation, transmission and distribution infrastructure is old and therefore requires investment and modernisation to improve efficiency and reduce power losses. Many African countries experience electricity blackouts due to load shedding, particularly during peak demand periods. Generating electricity from petrol- or diesel-fired plants is expensive but is commonly employed to meet this shortfall.

Electricity tariffs in many African countries do not reflect the market costs of production. Electricity markets have had to be liberalised in many countries in order to attract private investment. Market liberalisation has therefore necessitated higher prices to reflect market production costs. Unbundling of generation, transmission and distribution also means that terms of access to the transmission grid can be developed and provided to private Independent Power Producers (IPP) without conflicts of interest. Reforms of the energy market, including privatisation, can also be implemented to improve efficiency and competition in power generation. The removal of electricity subsidies can help the broader economy achieve sound public finances.

Setting up an independent electricity regulatory agency is also an important step in the liberalisation of the electricity market. This means that regulatory policies can be developed, applied and enforced transparently, leaving the role of government to be policy development and execution. The development of broad energy strategies, coupled with ease of access to the electricity transmission grid and competition in electricity generation and distribution, can encourage Independent Power Producers (IPPs) to participate in renewable energy generation. Unfortunately, earlier reforms in the electricity market in SSA led to increased use of fossil-based generation rather than renewable energy, driven by the cost advantages of conventional energy. This needs to be addressed in energy reforms to encourage the uptake of renewable energy.

In summary, conventional energy-generating projects have historically outperformed renewable energy projects based solely on their financial profiles. This is no longer the case. Renewable energy projects are competitive in their own right. Their competitiveness improves further when their environmental and social benefits are factored in. Renewable energy projects can be developed in an off-grid, modular manner, particularly in rural areas, and should also prove attractive for improving energy access for the rural poor.

Finally, developing countries should implement electricity market reforms and establish a practical regulatory framework to encourage private-sector IPPs to invest in renewable energy. The market for the electricity generated can be guaranteed through feed-in tariffs, tax incentives, and subsidies. Provided that the private sector has assurances of an adequate legal and regulatory framework, coupled with sound, consistent policies, this will attract private-sector funding to enable the scale-up of investment in renewable energy projects.

7.2. *Policy Reforms Required in Developing Countries*

Renewable energy projects generally have high capital costs but lower operating costs than conventional energy projects. Investing in Africa also attracts considerable country, regulatory, commercial and market risks. Capital markets in Africa are underdeveloped, and bond markets are illiquid. Perceptions of high risk in Africa increase the cost of capital for investors in renewable energy projects. Renewable energy projects also tend to be smaller. Thus, transaction costs per kWh are much higher than for conventional projects. The lack of data on wind speeds and solar insolation means feasibility studies take much longer to complete. The lack of relevant data to inform economic feasibility, decision-making, siting, planning and financing decisions increases the risk and uncertainty faced by potential investors.

Fossil fuels attract considerable subsidies in developing countries, including tax breaks, research and development grants, and fuel price guarantees. This puts renewable energy project financing at a competitive disadvantage compared to conventional energy projects. Subsidies lower the costs of power generation from conventional means. Developing country governments in SSA should, as a matter of urgency, set out a clear vision for the contribution of renewable energy to the total energy mix, where this has not yet been done. Setting out clear, legally binding national targets demonstrates commitment, political will, and determination. This assures private sector investors that the national authorities have a clear trajectory towards green electricity.

Developing country governments should also gradually phase out subsidies that are enjoyed by electric power-generating companies using fossil fuels. Switching fossil fuel subsidies to renewables is justifiable as renewable energy projects bring social and environmental benefits. Removal of subsidies should be implemented in a way that does not disadvantage poor members of society (Menyeh et al., 2021). Removal of subsidies will also encourage energy efficiency in use and conservation. Removal of fossil-fuel subsidies can be controversial and poses a political challenge for most governments in SSA, as many stakeholders, including high-income groups, benefit from subsidised energy costs. Therefore, any reforms need effective planning, strong communication, and civic engagement to ensure they are gradual, socially and economically fair, and generally acceptable to the public.

Alongside renewable energy targets, governments should also set clear feed-in tariffs for renewable energy producers. Offering a guaranteed fixed price with a premium above the market production costs provides an output-based incentive for large-scale Independent Power Producers (IPPs). This can enhance the project's profitability and increase returns on investment. The introduction of feed-in tariffs reduces the uncertainty around energy prices and revenues, thereby improving project bankability. Although over 30 countries had feed-in tariffs in 2010, only four were in sub-Saharan Africa: Uganda, Kenya, Tanzania, and Mauritius. By 2021, only 14 African countries had feed-in tariffs. Even then, these had not been successful in increasing investment in renewable energy projects due to a weak regulatory framework.

Many electricity utility companies in developing countries are publicly owned. Governments should set clear, mandatory targets for utility companies to supply a given proportion of their electricity from renewable sources, as a regulatory requirement. Provided that there is transparency and competition in the awarding of contracts for renewable energy projects, auctions and feed-in tariffs, together with efficient procurement systems, are essential prerequisites for attracting private-sector capital into renewable energy generation.

7.3. *Financial Risks and Effective Mitigation Strategies*

Investors in renewable energy projects in SSA face several risks, including political, currency, and commercial risks. Commercial risks arise because state-owned utilities often have weak balance sheets and credit ratings. Their credit payment obligations under power purchase agreements cannot be guaranteed. Poor balance sheets and credit ratings result from poor billing and payment-collection systems and from prices that do not reflect the market production costs of energy.

Country and political risks include government expropriation, war and civil disorder, and breach of contract. These risks feature highly when international investors are making location decisions for foreign investments. International investors also rank prevailing legal systems and independence of the judiciary highly, as they need confidence that commercial contracts will be enforceable in the event of default. Foreign investors in renewable energy projects also face currency risks, including fluctuations in interest rates and foreign exchange risks. If development capital is borrowed from international money markets and designated in hard currency, investors face risks if revenues are designated in local currency. Money markets are underdeveloped in SSA, suggesting that hedging instruments denominated in local currencies may not be readily available.

Other risks include expropriation of funds or nationalisation of assets by developing country governments. Governments may also fail to honour their contractual obligations. Clauses seeking dispute resolution through international arbitration tribunals should be incorporated in any contracts. Investors also need to protect their investments from losses arising from war, terrorism, and civil disturbances. They also need guarantees against currency transfer restrictions and currency inconvertibility. Finally, governments may fail to honour their financial obligations or default on honouring guarantees provided to investors. Fortunately, all these risks are insurable through the Multilateral Insurance Guarantee Agency (MIGA) of the World Bank Group. The World Bank has operations in many developing countries, and it is therefore well diversified to mitigate the impacts of such risks.

8. Project-Related Risks in Renewable Energy Projects

8.1. Project Completion Risks

Renewable energy projects are capital-intensive, with time and cost overruns being recurrent concerns for investors and sponsors. Such overruns delay the capital recovery period and result in additional interest payments. They also affect the project's profitability. Extensions of time to the construction contractor may be justified due to unforeseen ground conditions. To mitigate these risks, date-specific and lump-sum contracts may be used, with the risk transferred to construction contractors. Construction contractors may also be required to provide performance guarantees. In any case, these risks are also insured.

8.2. Political Risks

Political risks arise from the project's exposure to changes in the political climate. A sitting government or a change in government may lead to the imposition of new taxes or excessive bureaucratic controls on the repatriation of profits, changes in laws that are discriminatory to the project, or, in the extreme, its expropriation. As already noted, such risks are insurable through multilateral agencies that can act as guarantors against unfavourable events.

8.3. Environmental Risks

Environmental campaigner actions and protestors can disrupt renewable energy projects during implementation. There are also concerns that wind projects can be risky because they affect land use and wildlife, including birds. Hydropower projects can affect river flow characteristics, including silt loading. Lenders in recent years have become increasingly concerned about environmental risks. Project sponsors must undertake environmental impact assessments and demonstrate full compliance with national legislation and international best-practice guidelines on environmental matters.

8.4. Market Risks

Market risks faced by investors in renewable energy projects take three forms. The first is that markets may be insufficient for the power generated. The second is that competition may arise from new power-generating companies entering the market. The third is that the tariffs set may be at levels that are not commensurate with electricity market production costs. These risks are generally addressed through an availability or capacity charge in the Power Purchase Agreements (PPAs). Offtake contracts usually include take-or-pay clauses. In other words, since electricity cannot be stored once generated, power distribution companies are required to pay for the power irrespective of whether they take it or not.

8.5. Financial Risks

The profitability of a renewable energy project may be affected by changes in interest rates, currency exchange rates or commodity prices of inputs. Currency exchange rate risks are usually allocated to the power purchasing entity. Financial derivative tools may be used to hedge against risks arising from changes in interest and currency exchange rates. The use of financial derivatives for risk hedging in renewable energy projects is addressed in the next section.

9. Using Derivatives in Financing Renewable Energy Projects in SSA

Techniques for hedging risks in renewable energy projects to protect lenders include insurance contracts, government guarantees, policy incentives such as feed-in tariffs, multilateral agency guarantees, and financial derivatives. A financial derivative instrument is an agreement between two parties to mitigate risks arising from, for example, changes in interest rates, exchange rates, project revenues, credit risks and production quantities such as hourly energy outputs.

In developing countries such as South Africa, India, or Thailand, with well-developed financial systems and capital markets, funding for domestic infrastructure projects in local currency can be raised through local and international banks and bond issues. However, most countries in SSA have undeveloped financial systems. Their capital markets are illiquid and cannot provide long-term financing in local currency for major projects. Instead, utility-scale renewable energy projects rely on external funding denominated in hard currency from multilateral development agencies, international banks and export credit agencies. Such loans also attract hard currency variable interest rates. Thus, when user fees for the electricity generated are designated in local currency, such investments are subject to risks arising from interest rate and currency exchange rate fluctuations.

If a renewable energy project finance loan is designated in local currency at a fixed interest rate, there is no interest rate or currency risk. Where the infrastructure finance loan is denominated in local currency but offered at a variable interest rate, such a project is not exposed to foreign exchange risk. However, the risk of interest rate changes can be hedged through a local-currency interest rate swap.

If the project loan is denominated in a foreign currency at a fixed interest rate, there is no interest rate risk. However, the project faces currency exchange rate risk, which can be managed through offtake contracts or foreign currency swaps. Finally, when the project loan is denominated in a foreign currency and at a variable interest rate, the project faces both interest rate risk and currency exchange rate fluctuations. Interest rate risks in this case can be managed through hard-currency interest rate swaps. Furthermore, foreign exchange risks can be allocated through off-take contracts or hedged through cross-currency swaps.

Currency depreciation, which can lead to volatility in exchange rates, can materially impact a project's profitability and investment performance. This can also affect its ability to meet interest rate payment obligations and the ability to repay the loan.

Cross-currency derivative products are generally traded over the counter and are available only from large international banks. Cross-currency derivative products with maturities commensurate with long-term financing for renewable energy projects are generally unavailable in SSA financial markets. Most hedging for cross-currency risks is available for the short- to medium-term, particularly during the construction period.

Local market characteristics and the extent of capital market development influence the availability of over-the-counter (OTC) derivatives in financing packages for large renewable energy projects. Most developing countries in SSA have weak capital markets with poor liquidity. In such markets, there is a significant gap between the financing of renewable energy projects and the availability of hedging solutions to manage currency risks. Over-the-counter currency swaps and interest rate swaps, when available, are costly, which adds considerably to the required rates of return on capital to invest in such projects.

10. Strategies to Address the Renewable Energy Financing Gap

There is currently a massive infrastructure financing gap, particularly for renewable energy projects in developing countries, estimated at USD 1.5 trillion per annum (World Bank, 2024). Closing this gap requires a multi-pronged approach. Investors perceive infrastructure projects in developing countries, including renewable energy projects, as very risky. This deters private-sector participation and limits capital inflows into such projects. Borrowing in hard currencies also exposes developing countries to fluctuations in interest rates and exchange rates. However, hard-currency-denominated debt remains a significant burden and concern for many developing countries.

The financing gap could be narrowed by pursuing four strategies, namely:

- Improving project preparation and feasibility studies;
- Developing a stable macroeconomic framework, good governance and strengthening local capital markets;
- Leveraging the capacity of multilateral agencies to enhance global guarantees to de-risk renewable energy projects;
- Enhancing private sector participation in the development of energy projects.

Developing country governments in SSA should first and foremost focus on building local capacity among qualified, experienced infrastructure professionals to manage project execution and delivery processes, starting with feasibility studies. Well-prepared feasibility study reports and proposals during the initiation period are likely to improve project bankability. Developing a pipeline of bankable projects can enhance governments' credibility and attract private sector investment.

Collaboration with multilateral agencies will also assist developing countries with technical assistance, the development and enhancement of risk mitigation products, and the de-risking of projects, thereby making them more attractive to the private sector. It is estimated that enhanced de-risking of renewable energy projects by multilateral agencies, in collaboration with governments, can reduce the Levelised Cost of Electricity (LCOE) from renewable sources by USD 0.031 per kWh (Deloitte, 2023). Multilateral agencies can also assist developing countries by providing political risk cover, guarantees and insurance to reduce risks to the private sector. In addition, they can assist governments in developing policies that are favourable to attracting institutional investors, such as pension funds, insurance companies, and sovereign wealth funds.

Finally, closing the infrastructure financing gap will require developing countries to pursue sound macroeconomic policies, economic stability, low inflation and development of efficient and liquid local capital markets. Such markets will enable the mobilisation of domestic savings to provide long-term financing for clean energy development.

11. Conclusion and Further Research

Africa has vast renewable energy resources. It has enough renewable energy resources to meet its demand and also be a net exporter. However, renewable energy at present contributes very little to the electricity consumed in Africa. In any case, most of the renewable energy at present is hydropower. Because of population growth and expansion of electricity connectivity, electricity demand is expected to grow by up to 10% per annum between now and 2030. Six hundred forty-eight million SSAs lack access to electricity, and over 900 million lack access to clean cooking. Universal access to electricity in SSA is possible with an enabling policy framework and increased investment in innovative financing.

The work reported in this paper synthesises the barriers to financing renewable energy (RE) in Sub-Saharan Africa (SSA). It links them to a set of risk mitigation strategies, including market and regulatory reforms, project-related risk management, and the use of financial derivatives and multilateral guarantees. The originality of this work lies in bringing together the energy sector, project risk and financing, and perspectives on the use of financial derivatives into a single, SSA-focused framework. This work also frames the infrastructure financing gap explicitly in terms of local capital market development and de-risking strategies.

International investors in renewable energy projects in sub-Saharan Africa face several risks, including country, political, currency and commercial risks. These risks are insurable. The cost of utility-scale power generation from renewable energy sources has declined substantially over the last few years. However, developing country governments need to implement policy reforms, including setting clear, legally binding renewable energy targets to signal a clear commitment and build market confidence. They also need to develop technical capacity to identify suitable projects and undertake comprehensive feasibility studies to demonstrate bankability. Providing targeted grants may also be necessary, including the implementation of feed-in tariffs and competitive auctions. Removal of subsidies from conventional energy generation, bringing bankable projects to market, and working with multilateral agencies to de-risk them will reduce required capital rates of return and attract international financial investment. The author acknowledges the limitations of a literature-only analysis and the need to validate these recommendations empirically.

Renewable energy expansion in SSA will, in the short to medium term, require substantial financial resources from a range of sources, including public and private sources, grants and bilateral aid, and multilateral agency loans. In the long term, the huge financing gap can only be bridged by the development of efficient and liquid domestic capital markets to mobilise local savings. Additionally, it will be necessary to attract local institutional investors, such as pension funds and insurance companies, to support long-term financing for renewable energy development.

To unlock these investments, further research is required at the country level to collate stakeholder views on the required government policy changes, public perceptions and acceptance of various renewable energy technologies, and public willingness to pay for these investments. Further research should also survey the attitudes of international investors, energy companies, and developers regarding the changes needed to make the renewable energy sector in SSA more attractive to investment. Research on financing innovations to reduce the cost of capital required to accelerate investment in renewable energy in SSA is urgently needed.

References

African Union (2015). Agenda 2063: *The Africa We Want, African Union Commission*, Addis Ababa, ISBN: 978-92-95104-23-5.

Agyekum, E.B., Ali, E.B. and Kumar, N.M., 2021. Clean energies for Ghana—An empirical study on the level of social acceptance of renewable energy development and utilisation. *Sustainability*, 13(6), p.3114.

Bashir, M.J., Abdelhak, S., Salah, W.A. and Abuhelwa, M. (2024). Exploring public perception and willingness to pay for a renewable source of energy: evidence from an emerging economy of renewable-energy development. *Clean Energy*, 8(2), pp.177-188.

Boadu, S. and Otoo, E. (2024). A comprehensive review on wind energy in Africa: Challenges, benefits and recommendations. *Renewable and Sustainable Energy Reviews*, 191, p.114035.

Badu, E., Owusu-Manu, D.G., Edwards, D.J. and Holt, G.D. (2013). Analysis of strategic issues underpinning the innovative financing of infrastructure within developing countries. *Journal of Construction Engineering and Management*, 139(6), pp.726-737.

Brealey, R.A., Cooper, I.A. and Habib, M.A. (1996). Using project finance to fund infrastructure investments. *Journal of applied corporate finance*, 9(3), pp.25-39.

Climate Analytics (2022). *Renewable Energy Transition in sub-Saharan Africa*; available at https://climateanalytics.org/media/renewable_energy_transition_in_sub-saharan_africa.pdf, accessed on 24 January 2025.

Deloitte (2023) Financing the Green transition. November 2023, available at www.deloitte.com Accessed on 20 September 2025.

Estache, A., (2010). Infrastructure finance in developing countries: An overview. *EIB Papers*, 15(2), pp.60-88.

Esty, B.C., (2003). *Modern project finance: A casebook*. John Wiley & Sons, London.

Glaister, S. (2025). *The London Underground Public Private Partnership 1997-2010: No Way to Run a Railway*. Cambridge Scholars Publishing.

Grout, P.A. (1997). The economics of the private finance initiative. *Oxford Review of Economic Policy*, 13(4), pp.53-66.

International Renewable Energy Agency (2020). *Geothermal Development in Eastern Africa: Recommendations for power and direct use*, International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-268-0.

International Renewable Energy Agency (2021). Renewable Power Generation Costs in 2021, *International Renewable Energy Agency*, Abu Dhabi. ISBN 978-92-9260-452-3.

International Renewable Energy Agency and African Development Bank (2022). *Renewable Energy Market Analysis: Africa and Its Regions*, International Renewable Energy Agency and African Development Bank, Abu Dhabi and Abidjan. ISBN: 978-92-9260-417-2.

Ireri, B. and Shirley, R. (2021). Powering Growth, *Finance and Development*, September 2021, 62- 64.

KfW Development Bank (2020). *The Renewable Energy Transition in Africa: Powering Access, Resilience and Prosperity*, KfW Development Bank, Frankfurt.

Kensinger, J.W. and Martin, J.D. (1988). Project finance: Raising money the old-fashioned way. *Journal of Applied Corporate Finance*, 1(3), pp.69-81.

Komendantova, N., Patt, A., Barras, L. and Battaglini, A. (2012). Perception of risks in renewable energy projects: The case of concentrated solar power in North Africa. *Energy policy*, 40, pp.103-109.

Maqbool, R. and Akubo, S.A., (2022). Solar energy for sustainability in Africa: The challenges of socio-economic factors and technical complexities. International *Journal of Energy Research*, 46(12), pp.16336-16354.

Menyeh, B.O., (2021). Financing electricity access in Africa: A choice experiment study of household investor preferences for renewable energy investments in Ghana. *Renewable and Sustainable Energy Reviews*, 146, p.111132.

Moore, M.C. and Gutiérrez-Negrín, L.C., (2025). Project Permitting, Financing, and Economics of Geothermal Power Generation. In *Geothermal Power Generation* (pp. 571-607). Elsevier Science Ltd.

Namaswa, T., Githiomi, J., Oduor, N. and Kitheka, E., 2022. Sustainable biomass energy production and utilisation in sub-Saharan Africa: A case study of Kenya. *Journal of Horticulture and Forestry*, 14(4), pp.56-67.

Olando, S., Mwenda, M.N., Kikwatha, R. and Rambo, C.M. (2024). Effect of public-private partnership financing structure on completion of geothermal energy development projects in Kenya. *International Journal of Professional Business Review*: 9(11), pp. 1- 21.

Oluoch, S., Lal, P., Susaeta, A. and Vedwan, N., 2020. Assessment of public awareness, acceptance and attitudes towards renewable energy in Kenya. *Scientific African*, 9, p.e00512.

Sachs, J. D. (2015). *The Age of Sustainable Development*, Columbia University Press, New York.

Shah, S. and Thakor, A.V. (1987). Optimal capital structure and project financing. *Journal of Economic Theory*, 42(2), pp.209-243.

World Bank (2024). *Unlocking Local Finance For Sustainable Infrastructure*. Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/099091124150032446.

.

JCBM (2025) 8(S1) 72-87

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Factors Influencing Procurement in Construction: The Role of Clients and Construction Machinery in KwaZulu-Natal

Ayodeji Aiyetan[1], Kumar Dillip Das[2] and Blessing Ayodabo[3]

[1&3]Department of Construction Management and QS, Faculty of Engineering and the Built Environment, Durban University of Technology, South Affrica
[2]School of Civil Engineering, University of KwaZulu-Natal, South Africa

Received 07 October 2025; received in revised form 16 October 2025, 25 December 2025; accepted 27 December 2025
https://doi.org/10.15641/jcbm.8.S1.1930

Abstract

This study identifies the client and machinery-related factors and examines their interrelationships in construction procurement, employing a systems-thinking approach. Data from stakeholders (N=31) in the KwaZulu-Natal construction industry were collected through a survey using purposive sampling. The data were analysed using descriptive and inferential statistical methods, as well as Applied Systems Analysis (ASA), with causal loop diagrams (CLDs) illustrating how procurement performance evolves through reinforcing and balancing feedback loops. Findings indicate that clients' emphasis on cost and timely delivery strongly drives procurement decisions but can weaken decision-making, reduce communication, and increase project variations. Machinery-related challenges, including poor maintenance, high hiring costs, and limited access, further exacerbate inefficiencies. When considered together, balancing loops emerge, where strong governance, effective communication, preventive maintenance, and operator training stabilise and improve outcomes. The study contributes theoretically by advancing a systems-based perspective that integrates client governance and machinery management, and by identifying leverage points for policymakers, clients, and contractors, such as improving governance, embedding maintenance practices, aligning priorities with resource planning, and institutionalising feedback. Procurement effectiveness is thus shaped by interdependent governance, decision-making, resource management, and systemic learning.

Keywords: Applied Systems Analysis, Client, Construction, Machinery, Procurement, Governance

1. Introduction

The procurement process is a critical determinant of success in construction projects, covering activities from requirement identification through execution to closeout. Effective procurement ensures resources are secured and aligned with project objectives, while poor decisions often result in inefficiencies, delays, and cost overruns (Fleming, 2019). In construction, procurement is particularly complex due to the variety of available methods, competing trade-offs, and decision criteria shaped by project characteristics, client capabilities, and external constraints (Ruparathna & Hewage, 2015).

Clients play a central role in shaping procurement choices. Their technical expertise, prior experience, and willingness to assume responsibility significantly influence the selection of procurement methods (Plunkett, 2021). Experienced clients favour arrangements that provide greater involvement and control, whereas less experienced clients often prefer to transfer responsibility to contractors. Equally important are machinery-related factors: the availability, suitability, and operability of equipment strongly affect project feasibility and efficiency, particularly for complex projects requiring specialised tools. A lack of appropriate machinery not only threatens delivery but also constrains procurement strategy.

Despite extensive research on procurement practices, inefficiencies persist. Many approaches rely on linear cause-and-effect models, overlooking the interdependencies and feedback loops that shape outcomes. As a result, conventional strategies often fail

[1] Corresponding Author
Email address: ayodejia@dut.a.c.za

to address the dynamic and systemic nature of procurement challenges.

Existing research identifies several factors influencing procurement method selection, including project characteristics (time, cost, scope, and complexity), owner capacity, and risk-allocation preferences. Increasingly, multi-criteria decision-making tools such as the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP), along with related models, are employed to support these decisions (Suratkon et al., 2020; Franz & Leicht, 2016; Chen et al., 2016). However, while project- and risk-related drivers have received significant attention, client-specific characteristics and the availability of construction machinery remain underexplored. This gap is particularly relevant in regional contexts, such as KwaZulu-Natal, South Africa, where financial constraints, skill shortages, and limited resources significantly influence procurement performance.

Moreover, much of the existing literature has prioritised process optimisation and cost reduction, often neglecting the systemic and dynamic interactions that influence outcomes. Few frameworks capture causal feedback relationships or provide holistic strategies. This omission is critical, as project success depends on the interplay between client decision-making capacity and resource availability.

In response to this gap, the present study applies Applied Systems Analysis (ASA) to map causal feedback relationships within procurement systems and identify strategies to enhance procurement performance. By modelling the dynamic interactions among procurement variables, the research aims to generate actionable insights to improve efficiency, responsiveness, and overall organisational outcomes. Specifically, the study examines the influence of client-related and machinery-related factors on the selection of contract procurement methods in KwaZulu-Natal. By addressing these underexplored dimensions, the study seeks to align procurement strategies with client capacities and resource constraints, thereby supporting more effective and sustainable project delivery. Consequently, the four research questions (RQs)were investigated.

- RQ1: How do client-related factors and construction machinery considerations influence procurement method selection in KwaZulu-Natal?
- RQ2: What causal feedback relationships shape procurement performance?
- RQ3: How can ASA be applied to map and analyse these dynamics effectively?
- RQ4: What strategies, informed by a systems perspective, can enhance procurement methods and outcomes?

By integrating ASA, the research contributes a structured framework for identifying leverage points and designing interventions that address immediate inefficiencies while fostering long-term procurement improvements.

2. Literature Review

2.1. Procurement in Construction

Procurement in construction projects is a critical determinant of project success, as it involves acquiring goods and services essential to planning, execution, and closeout. More than purchasing, procurement encompasses relationship and contract management to ensure projects are delivered on time, within budget, and to the required standards. Its effectiveness directly impacts efficiency, cost control, and quality, making it a cornerstone of project performance.

Procurement provides the contractual framework through which clients engage participants to design, construct, and deliver facilities ready for use (Rowlinson, 2022). It secures competent contractors, ensures qualifications, and achieves services at reasonable cost (Fewings & Henjewele, 2019). Well-structured procurement reduces costly variations and delays, improving overall efficiency and outcomes.

The process typically unfolds in three stages: planning, execution, and closeout. Planning involves developing strategies, preparing tender documents, and evaluating bidders, setting the foundation by defining scope, cost, time, and quality requirements (Lester, 2014). Execution focuses on contract management, supplier evaluation, and negotiation, including requests for quotations, letters of intent, and purchase orders (Lester, 2014). Closeout ensures obligations are met, deliverables conform to standards, and handovers are correctly documented (Lester, 2014).

Procurement significantly shapes project outcomes. Timely procurement shortens schedules by streamlining supplier selection and contract administration (Basiru et al., 2022). Cost control is enhanced through efficient strategies, with automation and AI reducing processing times by over 30% in some organisations (Basiru et al., 2022). Quality is safeguarded by selecting qualified contractors and ensuring competitive pricing (Fewings & Henjewele, 2019). Efficiency is further strengthened by digitalisation and supplier relationship management, which support better decision-making (Basiru et al., 2022).

Despite its importance, procurement continues to face persistent challenges. Large projects with multiple stakeholders often involve complex processes that heighten risks and inefficiencies. Evolving methods, driven by technological innovation and sustainability goals, demand continuous adaptation. Nevertheless, robust procurement strategies remain vital to delivering cost-effective, timely, and high-quality construction outcomes.

2.2. Procurement Methods and Factors Influencing Construction

Procurement methods in construction are critical for project success, as they define execution frameworks, risk allocation, and stakeholder collaboration. Common approaches—traditional, design-build, and EPC (Engineering, Procurement, and Construction)—offer distinct advantages and challenges, making their selection a complex process. The choice depends on project characteristics, risk distribution, cost, schedule, and client preferences. To support decision-making, multi-criteria evaluation tools such as the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), TOPSIS, and Multi-Attribute Utility Theory (MAUT) are frequently employed (Soltanikarbaschi & Hammad, 2023; Liu et al., 2011; El-Sawalhi & Agha, 2017). Decision-making tools provide structured frameworks. For example, AHP derives weights for criteria based on client priorities (Soltanikarbaschi & Hammad, 2023; Liu et al., 2011), TOPSIS ranks alternatives against an ideal solution, and MAUT evaluates multiple criteria simultaneously, including cost and complexity (El-Sawalhi & Agha, 2017).

Several factors influence procurement in construction. Project size, type, and complexity dictate whether traditional or integrated approaches are more suitable, with larger projects favouring design-build or EPC frameworks (Zhong et al., 2022; El-Sawalhi & Agha, 2017). Risk allocation is also critical; design-build contracts often shift greater risk to contractors, while traditional methods distribute risks more evenly (Zhong et al., 2022; Bolomope et al., 2022). Budget and schedule considerations also matter, as design-build methods (which integrate design and construction under a single contract) can reduce costs and time by overlapping the design and construction phases (El Wardani et al., 2006). Client experience further influences decisions: experienced clients adopt innovative approaches, while less experienced clients tend to prefer traditional methods (El-Sawalhi & Agha, 2017).

Ultimately, no procurement method is universally superior. Achieving sustainability and efficiency in procurement requires careful assessment of project conditions, stakeholder goals, and market dynamics, supported by flexible, informed decision-making tools.

2.3. Client-Related Factors

Client-related factors in construction procurement are multifaceted, encompassing technical expertise, prior experience, and decision-making capacity, all of which significantly influence procurement selection and project performance. Client involvement in procurement processes is critical, enabling more informed decisions and improved project outcomes. Regional studies, particularly in KwaZulu-Natal, South Africa, highlight the importance of understanding local conditions, practices, and constraints (Aiyetan & Ayodabo, 2024).

Clients' technical expertise and experience are pivotal in selecting suitable procurement routes. Frameworks that incorporate clients' lived experiences and align procurement methods with project types can reduce cost overruns and delays, enhancing delivery (Bolomope et al., 2022). Client knowledge of procurement systems is positively correlated with performance outcomes, as those with a stronger understanding are more likely to achieve project objectives (Windapo et al., 2021). Evidence from Saudi Arabia supports this, demonstrating that knowledge, experience, and decision-making capacity are crucial for effective client involvement throughout project phases (Trigunarsyah & Al-Solaiman, 2015).

Active client involvement aligns project objectives with procurement choices. Effective briefing and selection processes contribute directly to achieving time, cost, and quality goals (Bowen et al., 1999). However, transitioning clients from passive funders to active participants has not constantly improved performance, highlighting the need for stronger organisational capabilities to support procurement decisions (Al-Harthi et al., 2014). In South Africa, the selection of a procurement system depends on both internal and external factors, with client knowledge and control being crucial for the successful implementation of such systems (Mathonsi & Thwala, 2012).

Context-specific studies emphasise tailoring procurement to local conditions. In KwaZulu-Natal, the project scope, budget, size, quality management, and risk management significantly influence the selection of procurement strategy (Aiyetan & Ayodabo, 2024). Broader South African studies also identify socio-economic factors, client requirements, capital cost, procurement policy, and project characteristics as key determinants, particularly across project phases (Mathonsi & Thwala, 2012).

Overall, client-related factors are central to procurement selection and project performance; however, integrating them effectively remains a challenge. The evolving role of clients demands strengthened internal structures and decision-making capabilities, yet improvements in project outcomes are not guaranteed, underscoring the need for ongoing research and development (Al-Harthi et al., 2014).

2.4. Construction Machinery Considerations

In construction procurement, machinery considerations are critical because they directly impact project efficiency, costs, and timelines. Selecting and managing equipment such as tower cranes, mobile cranes, concrete pumps, and excavators requires multi-criteria decision-making to optimise benefits and minimise challenges (Uğur, 2017). Effective equipment management—particularly in planning and selection—is vital for timely project completion, as it identifies necessary machinery, evaluates performance, and forecasts requirements (Chinchore & Khare, 2014).

Equipment selection must consider cost, productivity, and project-specific needs, since these strongly influence overall efficiency (Gates & Scarpa, 1980). Key factors include availability to prevent delays, suitability to match project requirements, and operational capacity to ensure efficient execution (Sakhare, 2024). Coordinated management enhances productivity and reduces downtime, especially in earthwork projects where soil types and environmental conditions affect schedules and budgets (Sakhare, 2024; Kumar & Mishra, 2024).

Procurement strategies must balance the ownership versus rental of machinery, considering idle time and long-term cost-effectiveness, including maintenance and lifecycle expenses (Gates & Scarpa, 1980; Fay et al., 2003). Efficient procurement also requires market analysis for advanced equipment and proper management of existing fleets (Sahu & Mohibullah, 2022).

Projects with specialised equipment face challenges such as downtime, operational inefficiencies, and cost overruns. Highway construction introduces complexities, including fuel supply, maintenance, and machinery transfer (Kumar & Mishra, 2024; Sahu & Mohibullah, 2022). Poor equipment management can be costly; one case study reported a 71.5% increase in costs and a 72% increase in project duration due to inadequate planning (Osman & Mohy, 2022). Addressing these issues through structured procurement strategies and comprehensive equipment planning is crucial to enhancing productivity, managing costs, and ensuring successful project delivery.

2.5. Systems Perspective in Procurement

Integrating systems thinking into construction procurement provides a holistic framework for understanding and improving procurement processes (Sterman, 2000). By examining interrelationships and feedback loops, systems thinking treats procurement as an interconnected system, rather than as a series of isolated activities, thereby enhancing decision-making and overall performance. In construction, where multiple stakeholders—including clients, contractors, and suppliers—interact, systems thinking helps identify and manage these interactions to improve efficiency and outcomes (Rowlinson & McDermott, 2005).

ASA complements this approach by providing structured tools for modelling and analysing complex systems, breaking them down into constituent parts and exploring their relationships (Barrad et al., 2018). ASA can model entire supply chains, revealing bottlenecks and inefficiencies, and supports informed decision-making (Ross-Smith & Yearworth, 2011). Feedback loops allow continuous assessment: positive loops amplify beneficial practices, while negative loops identify and mitigate risks (Barrad et al., 2018). Mapping causal relationships also clarifies how changes in one area affect others, helping to manage challenges such as cost overruns and schedule delays (Maulanisa et al., 2024).

ASA enables the simulation of scenarios to assess the impacts on project performance, thereby improving forecasting, resource allocation, and mitigation strategies for cost escalation and delays (Maulanisa et al., 2024; Love & Luo, 2018). It also supports performance tracking and auditing, helping projects remain on schedule and within budget (Ross-Smith & Yearworth, 2011).

Despite its advantages, implementing systems thinking and ASA is challenging due to project complexity, multiple stakeholders, and the dynamic construction environment. Adoption requires a cultural shift from linear to integrated approaches. Nevertheless, these methodologies offer substantial potential to enhance efficiency, inform decision-making, and improve outcomes in modern construction procurement.

2.6. Synthesis

Construction procurement has been conceptualised as a strategic and system-forming activity rather than a transactional process. The procurement of construction functionally structures contracts and manages risk, project objectives, and capabilities. It thus affects cost, time, quality, and overall performance. Inadequate construction procurement exacerbates delays, costs, and inefficiencies, whereas effective procurement strategies enhance coordination and predictability.

There is no superior procurement method; instead, efficiency depends on context, which is shaped by project complexity, risks, client capabilities, and market dynamics. The increasing Adoption of multi-criteria decision-making techniques suggests that making a procurement choice involves a multidimensional form of governance, rather than a purely technical act.

Factors relating to the client, most notably their knowledge, experience, and capacity for effective decision-making, clearly play a significant role in determining the level of purchasing success.

Nevertheless, increased client engagement does not necessarily contribute to better results without adequate capabilities being in place. Contingent-specific findings indicate that purchasing effectiveness is contextually entrenched in broader societal conditions. The procurement of machinery is another example of the systemic nature of procurement, as it directly affects productivity, costs, and schedules. Problems at this level of operations can feed into larger project inefficiencies.

A systems thinking perspective integrates these findings, considering procurement a complex adaptive system characterised by interdependencies and feedback. While systems-based approaches offer improved decision-making and risk management, their practical application remains constrained by organisational and cultural barriers. Overall, the literature reveals a persistent gap between recognising procurement as a strategic system and operationalising this understanding in practice.

3. Study context: Construction Industry in KwaZulu-Natal Province, South Africa

The construction industry in KwaZulu-Natal (KZN) plays a vital role in the provincial economy, although its contribution has declined in recent years. The sector accounted for approximately 2% of KZN's GDP in 2023/24, down from pre-2019 levels (KwaZulu-Natal Office of the Premier, 2024). In employment terms, KZN represents a substantial share of South Africa's construction workforce, with about 241,000 people employed in the third quarter of 2023 (Department of Employment and Labour, 2023). This underscores the industry's importance for job creation, despite persistent high unemployment, with official rates around 31% and expanded rates exceeding 44% (KwaZulu-Natal Office of the Premier, 2024).

The sector presents both opportunities and challenges. Infrastructure investments in transport, water, and civil works offer project prospects and have supported improvements in project awards (Industry Insight, 2025). However, project cancellations, postponements, cash-flow constraints, payment delays, rising input costs, and financial pressures undermine planning, resource allocation, and timely machinery procurement (Master Builders KwaZulu-Natal, 2024). Skills shortages and capacity constraints, particularly among small, medium, and micro-enterprises (SMMEs), further exacerbate inefficiencies, delays, and cost overruns (Ntuli & Allopi, 2014). Non-technical risks, including site invasions, intimidation, and procurement disputes, increase costs and erode investor confidence (Master Builders KwaZulu-Natal, 2024). Despite these challenges, KZN maintains a strong base of construction professionals in urban centres such as Durban and Pietermaritzburg.

Financial constraints and decision-making challenges among clients significantly affect procurement, often leading to delays in tendering, contract awards, and payments. Machinery availability and allocation—affected by cost pressures, late payments, or poor planning—also impact project execution. By analysing these client- and machinery-related factors using surveys, ASA, and causal loop diagrams, this study situates procurement challenges within KZN's broader construction dynamics.

Overall, the KZN construction industry combines opportunity and fragility. While it remains a key employer and infrastructure enabler, financial pressures, regulatory complexity, and external risks highlight the need for more resilient procurement systems to enhance project performance.

4. Research Methods

4.1. Data collection

Data for this study were collected using a structured questionnaire survey and a purposive sampling process designed to capture expert opinions on the research variables. A five-point Likert scale was used to measure the respondents' perceptions, allowing for both quantitative analysis and the expression of varying levels of agreement or importance. The Likert scale is widely adopted in construction management and social science research as it provides a reliable means of quantifying subjective judgments (Bryman, 2016).

A total of sixty-five (65) questionnaires were distributed to construction professionals in KwaZulu-Natal Province, South Africa. The targeted respondents included architects, quantity surveyors, project managers, contractors, finance and procurement professionals and engineers who were actively engaged in the construction industry. This ensured that the data were sourced from individuals with relevant expertise and direct involvement in construction projects, thereby enhancing the credibility and relevance of the findings (Fellows & Liu, 2015).

Of the 65 questionnaires, forty-five (45) were administered in person, facilitating direct engagement with respondents and reducing the likelihood of non-responses. Out of these, thirty-one (31) completed questionnaires were retrieved, representing a response rate of approximately 69%. This is considered acceptable for survey-based research in the construction management field, where response rates often range between 30% and 60% (Akintoye, 2000; Moser & Kalton, 2017). The achieved response rate indicates reasonable representativeness and suggests that the data obtained are reliable for analysis.

The adequacy of the sample size in survey research is often context-dependent. While the final number of usable responses (31) is modest, it is sufficient for exploratory analysis and for generating insights into professional perspectives within the provincial construction sector. Although the limited sample size may pose challenges for statistical inference, prior studies in construction management have reported similar or smaller sample sizes, especially when targeting experts in specific professional groups (Doloi, 2008). Moreover, the use of purposive sampling—targeting professionals with relevant expertise—ensures that the collected responses are highly informative, compensating for the relatively small sample size (Fellows & Liu, 2015).

Overall, the survey administration process, expert-based respondent selection, and acceptable response rate provide confidence in the validity of the data for subsequent analysis.

4.2. Data Analysis

The data collected through the questionnaire survey were analysed to investigate the influence of client-related and machinery-related factors on procurement in construction projects. Given that the responses were measured on a five-point Likert scale, descriptive statistics were used to summarise and interpret respondents' perceptions.

The primary statistical measures used were the Mean Score (Perception Index-PI), Standard Deviation (SD), Interquartile Range (IQR), and Coefficient of Variation (CoV). These measures provide complementary insights into the central tendency, variability, and consensus of professional opinions:

Perception Index: The mean score for each factor was computed to determine its relative importance as perceived by respondents. Higher mean values indicate stronger agreement on the factor's influence on procurement. This approach is widely adopted in construction management studies where Likert-scale responses are aggregated into a perception index to rank critical factors (Akintoye, 2000; Doloi, 2008).

Standard Deviation (SD): The standard deviation was calculated to assess the dispersion of responses around the mean. Lower SD values suggest greater consensus among respondents, whereas higher values indicate divergent opinions.

Interquartile Range (IQR): The IQR was used to further assess variability by focusing on the middle 50% of responses. This is particularly useful in Likert-based data, where extreme values can sometimes distort measures of variability. A smaller IQR reflects a tighter clustering of professional views, enhancing confidence in the ranking of the factors.

Coefficient of Variation (CoV): The CoV, expressed as the ratio of the standard deviation to the mean, was used as a relative measure of dispersion. By normalising the variability across different factors, the CoV allows for comparability between factors with different mean scores (Fellows & Liu, 2015).

A further non-parametric test (Chi-square test p-values) was conducted to examine whether the observed distribution of Likert-scale responses for each factor differed significantly from a uniform (random) distribution. The null hypothesis (H_0) for each factor was that respondents' ratings were evenly distributed across the Likert scale, implying no consensus regarding the factor's influence on procurement. Rejection of H_0 ($p < 0.05$) therefore indicates that the observed responses were not random and that there was statistically significant agreement among respondents regarding the importance of that factor. The Chi-square test was not used as a test of independence between variables, but rather as a supporting test of response consistency and consensus, complementing the descriptive statistics.

The use of these combined statistical measures ensured not only the identification of the most influential client and machinery factors but also the assessment of the consistency of expert judgments. Factors with higher mean scores and lower variability (low SD, narrow IQR, smaller CoV, and p-values less than 0.05) were considered both significant and stable in terms of respondent agreement.

The ranked perception indices and associated measures were subsequently integrated into ASA-linked causal loop diagrams, enabling the mapping of interrelationships between procurement-related factors. This approach facilitated the development of causal feedback structures within the construction procurement system, providing deeper insights into how client- and machinery-related drivers interact dynamically to influence project outcomes.

4.3. ASA for crafting CLDs

To examine the dynamic interrelationships between client- and machinery-related factors affecting construction procurement, this study employed the Applied Systems Analysis (ASA) method. ASA integrates expert-based data with systems thinking tools to conceptualise and analyse complex management problems (Checkland, 1999; Sterman, 2000).

ASA is particularly suited for construction procurement, which involves multiple stakeholders, competing objectives, and resource interdependencies.

It provides a holistic view of interconnected factors rather than treating them in isolation (Williams, 2005). ASA also enables the integration of quantitative data with qualitative insights, combining measurable variables (e.g., machinery availability) with judgment-based factors (e.g., client decision-making flexibility)

(Checkland, 1999; Fellows & Liu, 2015).

A key advantage of ASA is its dynamic perspective: causal loop diagrams (CLDs) capture feedback mechanisms and time delays, revealing not only which factors are influential but also how they interact over time (Sterman, 2000). The visual representation of procurement drivers also serves as a practical decision-support tool, helping practitioners anticipate unintended consequences and identify leverage points for improving performance (Forrester, 1961).

In this study, construction procurement was conceptualised as a system of interacting factors, rather than as a linear sequence of activities. Survey data—including mean PIs, SDs, IQR, and CoVs—were analysed to inform the ASA process by identifying critical factors and assessing levels of stakeholder consensus and uncertainty. These quantitative insights guided the development of CLDs, which illustrate how client requirements, decision-making behaviours, and machinery availability interact through reinforcing and balancing feedback loops to shape procurement outcomes (Forrester, 1961; Williams, 2005).

The CLDs were developed using a theory-informed, data-driven analytical approach, rather than through direct respondent validation methods such as group model building. Following the quantitative analysis, the authors constructed diagrams by integrating empirical findings from the questionnaire survey (including ranked perception indices and measures of variability), established literature on construction procurement and systems thinking, and expert judgement grounded in prior research and domain knowledge.

Although respondents did not directly validate the CLDs, their aggregated perceptions provided a robust empirical basis for factor selection and prioritisation. At the same time, ASA principles were used to interpret and formalise the causal relationships.

The CLD development process was systematic and iterative. Client-related and machinery-related factors were initially identified through a comprehensive literature review and subsequently refined using survey data. Factors were prioritised based on PI values, supported by measures of response consistency. Initial cause–and–effect relationships were then established by combining empirical rankings with theoretical insights and logical reasoning consistent with construction practice.

The resulting causal structures were iteratively refined to enhance internal consistency, logical coherence, and alignment with real-world procurement dynamics, including the identification of reinforcing and balancing feedback loops.

The final CLDs were embedded within an ASA framework to represent construction procurement as a dynamic system, enabling analysis of the interactions between client- and machinery-related factors and their cumulative effects on construction project outcomes.

Causal relationships were assigned polarities: positive (+) indicates a direct relationship, and negative (–) indicates an inverse relationship (Sterman, 2000). Reinforcing loops amplify changes, such as increased client demands intensifying procurement delays, while balancing loops stabilise the system, for example, timely machinery allocation mitigating delays. Including both loop types provides a nuanced understanding of how procurement performance evolves, highlighting persistent challenges and mechanisms for control.

Overall, ASA offers a rigorous, systems-oriented framework that situates client- and machinery-related factors within a dynamic causal structure, moving beyond simple factor rankings to provide both analytical insights and practical guidance for enhancing procurement effectiveness in construction projects.

5. Results and Discussion

5.1. Profile of respondents

Table 1 presents the profile of respondents, reflecting a balanced and diverse representation of stakeholders in KwaZulu-Natal's construction sector.

Project Managers constituted the largest group (22.58%), followed by Contractors (19.35%), Engineers (16.13%), Architects (12.90%), Clients (19.35%), and Quantity Surveyors (9.68%). Most respondents held a bachelor's degree (45.16%), with 35.48% having a diploma and 19.35% possessing honours or postgraduate qualifications, indicating strong academic grounding. In terms of professional experience, the majority reported 11–15 years (70.97%), followed by 5–10 years (19.35%) and over 16 years (9.68%), demonstrating substantial expertise. This combination of diverse roles, qualifications, and experience ensures that both professional and client perspectives are captured, enhancing the credibility and validity of the study's findings.

Table 1: Profile of respondents

Respondent's profile	Number	Per cent
Type of respondents		
Architects	4	12.90
Quantity Surveyors	3	9.68
Clients	4	12.90
Project Managers	7	22.58
Contractors	6	19.35
Clients	2	6.45
Engineers	5	16.13
Total	31	100
Qualification		
Diploma	11	35.48
Bachelors	14	45.16
Honours and Postgraduate	6	19.35
Total	31	
Experience		
5-10 years	6	19.35
11-15 years	22	70.97
>16 years	3	9.68
Total	31	100

5.2. Client-linked factors influencing procurement in construction

Table 2 presents Client-linked factors influencing procurement in construction. Client-linked factors influencing procurement revealed that cost and time are the most critical considerations. Among client-linked factors, the client's emphasis on low construction cost was rated the most influential, with a high mean score of (4.61), a relatively low standard deviation (SD) of (0.495), a CoV of (10.7%), an IQR of (1.0), and a p-value of (0.281). This demonstrates broad agreement among respondents that cost considerations dominate procurement choices. Similarly, the client's emphasis on timely project delivery was also critical, recording a mean of (4.39), SD (0.667), CoV (15.2%), IQR (1.0), and a significant p-value of (0.018). These two factors confirm that clients primarily drive procurement decisions based on affordability and completion speed.

Moderately influential was the type of client's funding, with a mean of (3.94), SD (0.814), CoV (20.7%), IQR (2.0), and p-value (0.879). This suggests the funding source is less significant compared to cost and time. In contrast, several client factors scored notably lower. The client's ability to brief was recorded as a mean of (2.74), SD (0.682), CoV (24.9%), IQR (1.0), and p-value (0.044), highlighting limitations in articulating project requirements. The client's ability to make decisions scored even lower at (2.48), SD (0.677), CoV (27.2%), IQR (1.0), and a highly significant p-value of (<0.001), underscoring decision-making as a critical weakness. Likewise, the client's contribution to design

Table 2: Client-linked factors influencing procurement in construction

S/N	Factor	Mean score	Standard deviation	CoV	IQR	p-Values
1	Client's emphasis on timely project delivery	4.39	0.667	15.2	1.0	0.018
2	Client's emphasis on low construction cost	4.61	0.495	10.7	1.0	0.281
3	Type of client's funding	3.94	0.814	20.7	2.0	0.879
4	The client's ability to brief the procurement team	2.74	0.682	24.9	1.0	0.044
5	Client's ability to make a decision	2.48	0.677	27.2	1.0	<0.001
6	Client's contribution to design and construction	2.39	0.667	28.0	1.0	0.018
7	Client's experience in construction	1.87	0.619	33.1	1.0	0.003

and construction registered a mean of (2.39), SD (0.667), CoV (28.0%), IQR (1.0), and p-value (0.018). In contrast, the client's prior experience in construction was rated the lowest with a mean of (1.87), SD (0.619), CoV (33.1%), IQR (1.0), and p-value (0.003).

Collectively, these results indicate that although cost and time dominate procurement priorities, weak technical capacity, poor decision-making, and limited client involvement pose significant challenges to procurement effectiveness.

5.3. Machinery-linked factors influencing procurement in construction

Table 3 presents machinery-linked factors influencing procurement in construction. These factors were also highlighted as significant constraints on procurement. Poor maintenance of tools and machinery emerged as the most pressing issue with a mean score of (4.55), SD (0.568), CoV (12.5%), IQR (1.0), and a highly significant p-value (<0.001). This was closely followed by difficulties in hiring construction tools and machinery (mean = 4.52; SD = 0.570; CoV = 12.6%; IQR = 1.0; p = 0.001), and the increase in hiring costs (mean = 4.45; SD = 0.723; CoV = 16.2%; IQR = 1.0; p = 0.008). These factors confirm that affordability and access to machinery are substantial barriers. Inadequate skills of machinery operators were also rated high (mean = 4.35; SD = 0.661; CoV = 15.2%; IQR = 1.0; p = 0.020), as was the insufficient number of machines available on-site (mean = 4.29; SD = 0.739; CoV = 17.2%; IQR = 1.0; p = 0.115), pointing to operational inefficiencies in equipment management.

Table 3: Machinery-linked factors influencing procurement in construction

S/N	Factor	Mean score	Standard deviation	CoV	IQR	p-values
1	Poor maintenance of tools and machinery	4.55	0.568	12.5	1.0	<0.001
2	Difficulties in hiring construction tools and machinery	4.52	0.570	12.6	1.0	0.001
3	Increase in the hiring cost of construction machinery	4.45	0.723	16.2	1.0	0.008
4	Inadequate skills of the machinery operator	4.35	0.661	15.2	1.0	0.020
5	Insufficient number of machinery available on-site	4.29	0.739	17.2	1.0	0.115
6	Damage to tools and machinery	4.16	0.583	14.0	1.0	<0.001
7	Absolute machinery used in construction operations	2.58	0.564	21.9	1.0	0.008
8	Complexities in the operation of machinery	1.84	0.638	34.7	1.0	<0.001*

*Asymptotic significance is displayed

Other machinery-linked concerns, though rated lower, remain relevant. Damage to tools and machinery was noted with a mean of (4.16), SD (0.583), CoV (14.0%), IQR (1.0), and a significant p-value (<0.001). Meanwhile, absolute (outdated) machinery scored much lower at (2.58; SD = 0.564; CoV = 21.9%; IQR = 1.0; p = 0.008), and complexities in machinery operations were rated the least influential (mean = 1.84; SD = 0.638; CoV = 34.7%; IQR = 1.0; p < 0.001).

These findings indicate that the core machinery-related challenges are less about outdated or overly complex equipment and more about affordability, accessibility, maintenance, and operator competence.

5.4. Conceptual Frameworks using CLDs based on Systems Thinking

5.4.1. Client-Related Factors and Feedback Loops

Client-related factors play a central role in determining procurement performance in construction projects. The reinforcing loop (R1 – Pressure Loop) illustrates how a client's emphasis on low costs and fast delivery, while initially beneficial, may create unintended negative consequences (Figure 1: The Client-Related CLD). Increased pressure for affordability and timeliness results in tighter procurement schedules, which often weaken decision-making capacity. This leads to project variations that cause delays and overruns, further intensifying cost and time pressures and perpetuating a cycle of inefficiency that negatively affects procurement.

In contrast, the balancing loop (B1 – Governance Loop) demonstrates the stabilising influence of effective governance and communication. Strong client governance fosters clear communication and integration with contractors, thereby improving procurement alignment, reducing delays, and enhancing procurement outcomes (Figure 1: The Client-Related CLD) (Watermeyer, 2022; Jagtap, Kamble, & Raut, 2017; De Blois et al., 2011).

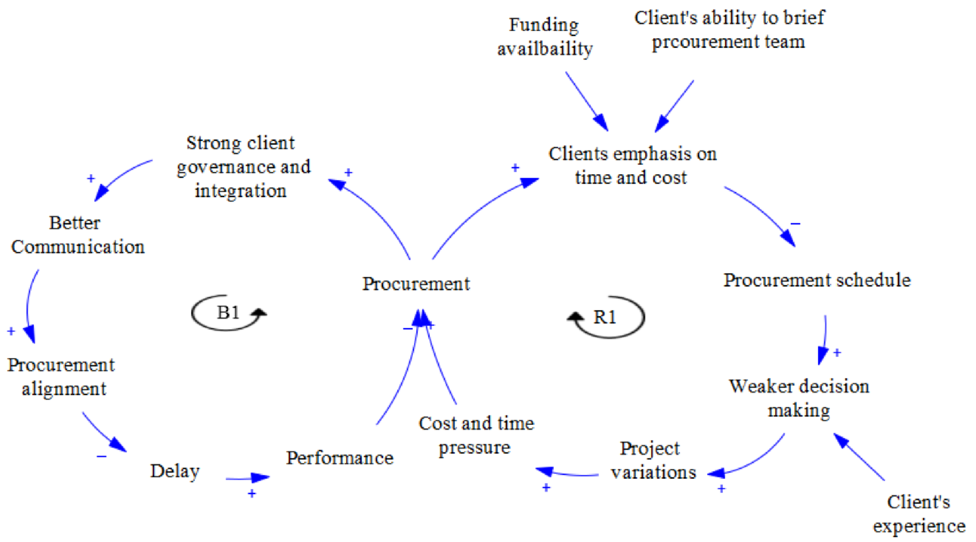

Figure 1: The Client-Related CLD

5.4.2. Machinery-Related Factors and Feedback Loops

Machinery availability, affordability, and maintenance are equally critical to procurement performance. The reinforcing loop (R2 – Cost-Access Loop) illustrates how high equipment hiring costs limit access to machinery, resulting in delays and overruns that, in turn, exacerbate cost pressures (Figure 2: The Machinery-Related CLD). This creates a cycle of inefficiency in resource utilisation.

The balancing loop (B2 – Capacity Loop) demonstrates, however, that proper maintenance practices and skilled operators significantly improve efficiency. These factors reduce downtime and delays, thereby stabilising procurement (Figure 2: The Machinery-Related CLD) (Samee & Pongpeng, 2016; Osman & Mohy, 2022).

5.4.3. Integrated Client–Machinery Interplay

The integrated CLD reveals the dynamic interplay between client and machinery-related factors. The reinforcing loop (R3 – Misalignment Loop) highlights how client priorities and weak client decision-making undermine machinery planning, leading to delays, a

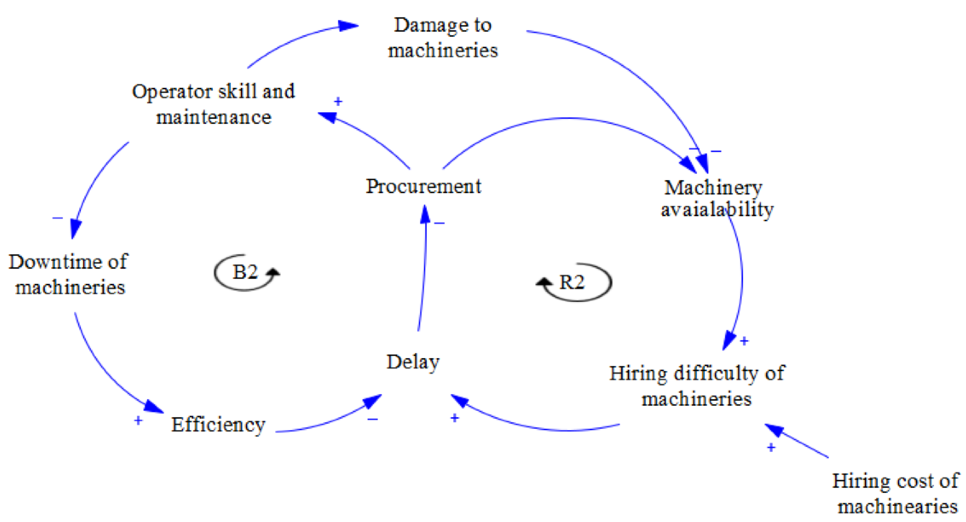

Figure 2: The Machinery-Related CLD

downward spiral of inefficiency, and a negative impact on procurement (Figure 3: The Integrated CLD).

affordability and timely delivery as the most influential considerations (mean scores>4.0). This aligns with

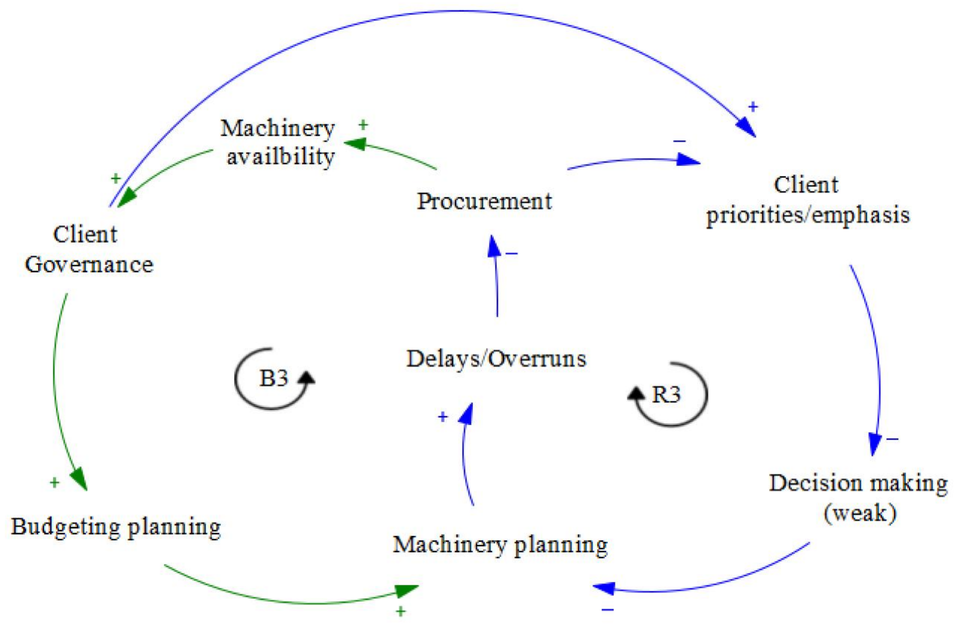

Figure 3: The Integrated CLD.

Conversely, the balancing loop (B3 – Strategic Integration Loop) demonstrates how robust client governance strengthens machinery budgeting and planning, ensuring that machinery planning improves procurement and enhances equipment availability (Figure 3: The Integrated CLD) (Al-Bayati et al., 2023; Lam & Gale, 2023)

The CLDs show that procurement outcomes are driven by reinforcing loops that amplify inefficiencies and balancing loops that stabilise performance. Strengthening balancing loops (B1–B3) and weakening reinforcing loops (R1–R3) through enhanced client governance, improved communication, effective machinery management, and systemic learning can transform procurement into a resilient, efficient, and value-driven process.

6. Discussion

The findings from this study reveal that both client-related and machinery-related factors significantly influence the effectiveness of procurement systems in construction. When interpreted through the conceptual framework developed using ASA and CLDs, these findings illuminate the dynamic feedback structures that underlie procurement performance.

6.1. Client-Related Dynamics in Procurement

The results indicate that clients' emphasis on cost and time dominates procurement decision-making, with prior studies that highlight clients' prioritisation of short-term cost savings and schedule adherence over broader value considerations (Bowen et al., 1999; Watermeyer, 2022). However, the study also found significant weaknesses in client decision-making capacity, briefing ability, and technical experience, with mean scores below 3.0. These weaknesses resonate with earlier work suggesting that limited client expertise and involvement contribute to procurement inefficiencies and project delays (Al-Harthi et al., 2014; Trigunarsyah & Al-Solaiman, 2015).

The reinforcing Loop (R1 – Pressure Loop) explains this pattern: intensified cost and time pressures strain decision-making capacity, leading to increased variations and undermining performance. In contrast, the balancing loop (B1 – Governance Loop) suggests that stronger governance and communication can mitigate these effects by enhancing alignment and coordination (Figure 1). This highlights that interventions aimed at strengthening governance, decision-making skills, and integration mechanisms are essential leverage points for stabilising procurement outcomes.

6.2. Machinery-Related Dynamics in Procurement

Machinery-related findings emphasise affordability and accessibility challenges. Poor maintenance, difficulties in hiring, and rising costs (PIs>4.0) were rated as critical barriers. These findings support the literature emphasising the importance of equipment availability, maintenance, and lifecycle management in ensuring project success (Chinchore & Khare, 2014; Samee & Pongpeng, 2016). Moreover, outdated or complex machinery was not viewed as a significant issue, suggesting that the immediate challenge lies less in adopting technology and more in ensuring operational reliability and access.

The reinforcing loop (R2 – Cost-Access Loop) captures a systemic explanation: high hire costs reduce availability, triggering delays that further intensify cost pressures. The balancing loop (B2 - Capacity Loop) demonstrates that preventive maintenance and operator competence can stabilise system performance by reducing downtime (Figure 2), consistent with evidence linking maintenance and training to productivity gains (Osman & Mohy, 2022).

6.3. Integrated Client–Machinery Interplay

The integration of client and machinery factors reveals a critical finding: client decision-making weaknesses exacerbate machinery procurement challenges. Weak governance and poor planning lead to insufficient machinery allocation, delays, and dissatisfaction, which reinforce client–contractor tensions. This reflects the reinforcing loop (R3 – Misalignment Loop) in the framework, where misaligned priorities perpetuate inefficiencies. On the other hand, the balancing loop (B3 – Strategic Integration Loop) illustrates how strong governance, strategic budgeting, and planning for machinery availability can enhance performance and foster positive cycles of satisfaction and governance reinforcement (Figure 3).

This interplay resonates with recent literature emphasising the need for procurement approaches that integrate both client-side governance and resource-side management (Lam & Gale, 2023; Al-Bayati et al., 2023). It suggests that focusing on a single dimension (e.g., client governance without addressing machinery access) is insufficient for sustainable procurement improvement.

6.4. Leverage Points in the Procurement System

From the CLDs, several leverage points emerge where targeted interventions can yield significant systemic improvements:

***Strengthening Client Governance and Decision-Making Capacity*:** Weak decision-making reinforces inefficiencies (R1, R3). Capacity-building initiatives, improved training, and structured governance frameworks reduce project variations and delays (Watermeyer, 2022).

***Enhancing Communication and Integration*:** Strengthening the governance loop (B1) requires improved communication between clients and contractors. Joint planning workshops, digital coordination platforms, and trust-building mechanisms mitigate adversarial dynamics (De Blois et al., 2011).

***Optimising Machinery Procurement and Maintenance*:** Addressing and reinforcing inefficiencies in machinery (R2) requires preventive maintenance, operator training, and lifecycle cost planning. These interventions stabilise procurement outcomes by improving efficiency (Samee & Pongpeng, 2016; Osman & Mohy, 2022).

***Aligning Client Priorities with Resource Planning*:** Using multi-criteria decision-making tools ensures procurement decisions balance cost, time, and machinery needs, mitigating misalignment (Soltanikarbaschi & Hammad, 2023).

***Institutionalising Feedback and Learning*:** Strengthening balancing loops depends on systematic feedback. Post-project reviews and knowledge management practices embed lessons learned into future procurement decisions (Love & Luo, 2018).

6.5. Implications for Research and Practice

The findings, interpreted through the systems-based framework, yield several implications:

6.5.1. Theoretical Implications

This study advances procurement research by adopting a systemic perspective, highlighting how reinforcing and balancing loops link cost pressures, decision-making, and machinery management. By integrating client- and machinery-related factors, it addresses a literature gap, moving beyond isolated analyses of governance or equipment management (Ruparathna & Hewage, 2015; Bolomope et al., 2022).

6.5.2. Practical Implications

Strengthening client governance and decision-making is a priority, with training, procurement guidelines, and institutional reforms serving as leverage points to break reinforcing inefficiency loops. Investment in machinery maintenance and operator training, including preventive maintenance and lifecycle planning, stabilises procurement performance. Integrating governance with machinery planning using multi-criteria decision-making tools (AHP, TOPSIS) balances cost, quality, and resources (Soltanikarbaschi & Hammad, 2023). Systematic feedback, through post-project reviews and knowledge management, strengthens balancing loops and improves procurement practices (Love & Luo, 2018).

7. Conclusion

This study examined the interrelationships between client- and machinery-related factors in construction procurement using a systems-thinking approach. By integrating survey findings from the KwaZulu-Natal

construction industry with CLDs, a dynamic understanding of how procurement performance evolves through reinforcing and balancing feedback loops was provided.
Results confirm that clients' focus on cost and timely delivery strongly drives procurement decisions, but these priorities often weaken decision-making capacity, reduce communication, and increase project variations. Machinery-related challenges—including poor maintenance, high hiring costs, and limited access—also exert pressures on project efficiency. Considered in isolation, these factors reinforce inefficiencies. However, when viewed through a systems lens, balancing loops emerge: strong governance, effective communication, preventive maintenance, and operator training stabilise and improve procurement outcomes.

The study contributes both theoretically and practically. It advances procurement research by moving beyond linear analyses to a systems-based perspective, highlighting the dynamic interaction between client governance and machinery management. It addresses a literature gap by integrating these dimensions, which are often studied separately. Practically, it identifies leverage points for policymakers, clients, and contractors: strengthening governance and decision-making, embedding preventive maintenance, aligning client priorities with resource planning, and institutionalising lessons learned through feedback systems. By combining empirical evidence with systems thinking, the study demonstrates that procurement effectiveness depends on interdependent governance, decision-making, resource availability, and feedback learning rather than cost control alone.

Limitations include the single-provincial context, which may restrict generalisability, and the reliance on perceptual survey data, suggesting a need for triangulation with project performance records or longitudinal studies. Future research should apply ASA and CLDs across diverse regions and project types, test interventions at leverage points, and explore digital technologies like BIM and predictive analytics to enhance machinery management. Overall, the study demonstrates that effective procurement stems from dynamic governance, decision-making, machinery, and systemic learning, providing a pathway to resilient, efficient, and value-driven construction procurement systems.

References

Aiyetan, A. O., & Ayodabo, B. (2024). Project and management scope factors influencing the selection of contract procurement method in the KwaZulu-Natal construction industry. In I. Musonda, E. Mwanaumo, A. Onososen, & R. Kalaoane (Eds.), *Development and investment in infrastructure in developing countries: A 10-year reflection* (pp. 596–602). Routledge. https://doi.org/10.1201/9781003483519-64

Akintoye, A. (2000). Analysis of factors influencing project cost estimating practice. *Construction Management and Economics*, *18*(1), 77–89.

Al-Bayati, A. J., Kelly, D., Hasanzadeh, S., & York, D. D. (2023). Practitioners' views concerning the causal effects of project delivery methods and procurement methods on construction projects. *Practice Periodical on Structural Design and Construction*, *28*(1). https://doi.org/10.1061/(asce)sc.1943-5576.0000742

Aldhaheri, M. A. (2017). *Client causes of variation in construction projects in the United Arab Emirates* [Master's thesis, The British University in Dubai]. BUiD Institutional Repository. https://bspace.buid.ac.ae/handle/1234/1080

Al-Harthi, A., Soetanto, R., & Edum-Fotwe, F. (2014). *Revisiting client roles and capabilities in construction procurement* [Conference contribution]. Loughborough University. https://hdl.handle.net/2134/16525

Barrad, S., Valverde, R., & Gagnon, S. (2018). The application of system dynamics for a sustainable procurement operation. In H. Qudrat-Ullah (Ed.), *Innovative solutions for sustainable supply chains* (pp. 179–196). Springer, Cham. https://doi.org/10.1007/978-3-319-94322-0_7

Basiru, J. O., Ejiofor, C. L., Onukwulu, E. C., & Attah, R. U. (2022). Streamlining procurement processes in engineering and construction companies: A comparative analysis of best practices. *Magna Scientia Advanced Research and Reviews*, *6*(1), 118–135. https://doi.org/10.30574/msarr.2022.6.1.0073

Bolomope, M., Amidu, A. R., Ajayi, S. O., & Javed, A. A. (2022). Decision-making framework for construction clients in selecting appropriate procurement route. *Buildings*, *12*(12), 2192. https://doi.org/10.3390/buildings12122192

Bowen, P., Pearl, R. G., & Edwards, P. J. (1999). Client briefing processes and procurement method selection: A South African study. *Engineering, Construction and Architectural Management*, *6*(2), 91–104. https://doi.org/10.1108/EB021102

Bryman, A. (2016). *Social research methods* (5th ed.). Oxford University Press.

Checkland, P. (1999). *Systems thinking, systems practice*. Wiley.

Chen, Q., Xia, B., Jin, Z., Wu, P., & Hu, Y. (2016). Choosing appropriate contract methods for design-build projects. *Journal of Management in Engineering*, *32*(6), 04016017. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000473

Chinchore, N. D., & Khare, P. R. (2014). Planning and selection of heavy construction equipment in civil engineering. *International Journal of Engineering Research and Applications*, *4*(12, Part 1), 29–31.

De Blois, M., Herazo-Cueto, B., Latunova, I., & Lizarralde, G. (2011). Relationships between construction clients and participants of the building industry: Structures and mechanisms of coordination and communication. *Architectural Engineering and Design Management*, *7*(1), 3–22. https://doi.org/10.3763/AEDM.2009.0110

Department of Employment and Labour. (2023). *Construction remains one of the high-risk sectors in South Africa – Deputy Minister Jomo Sibiya*. Government of South Africa.

Doloi, H. (2008). Application of AHP in improving construction productivity from a management perspective. *Construction Management and Economics*, *26*(8), 841–854.

El-Sawalhi, N. I., & El Agha, O. (2017). Multi-attribute utility theory for selecting an appropriate procurement method in the construction projects. *Journal of Construction in Developing Countries*, *22*(1), 75–96. https://doi.org/10.21315/JCDC2017.22.1.5

El Wardani, M. A., Messner, J., & Horman, M. J. (2006). Comparing procurement methods for design-build projects. *Journal of Construction Engineering and Management*, *132*(3), 230–238. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:3(230)

Fay, M. J., Hansen, C. M., Zuchristian, C. M., & Blaxton, A. C. (2003). *An analysis of USMC heavy construction equipment (HCE) requirements* [Master's thesis, Naval Postgraduate School]. Defense Technical Information Center.

Fellows, R., & Liu, A. (2015). *Research methods for construction* (4th ed.). Wiley-Blackwell.

Fewings, P., & Henjewele, C. (2019). Construction procurement. In P. Fewings & C. Henjewele (Eds.), *Construction project management: An integrated approach* (3rd ed., p. 30). Routledge.

Fleming, Q. W. (2019). Project procurement management: Contracting, subcontracting, teaming. Project Management Institute.

Forrester, J. W. (1961). *Industrial dynamics*. MIT Press.

Franz, B., & Leicht, R. (2016). An alternative classification of project delivery methods used in the United States building construction industry. *Construction Management and Economics*, *34*(10), 683–694. https://doi.org/10.1080/01446193.2016.1265814

Gates, M., & Scarpa, A. (1980). Criteria for the selection of construction equipment. *Journal of the Construction Division*, *106*(2), 207–219. https://doi.org/10.1061/JCCEAZ.0000878

Industry Insight. (2025). *Construction Monitor: March 2025 (Market Intelligence Report*). Industry Insight.

Jagtap, M., Kamble, S. S., & Raut, R. D. (2017). An empirical examination of the procurement-led supply chain in the construction industry. *International Journal of Procurement Management*, *10*(1), 1–26. https://doi.org/10.1504/IJPM.2017.080981

Kumar, A., & Mishra, B. (2024). An analytical review for the search of optimal selection & utilisation of earthwork equipment in construction. *International Journal of Emerging Science and Engineering*, *12*(11), 1–9. https://doi.org/10.35940/ijese.k2587.12111024

KwaZulu-Natal Office of the Premier. (2024). *Annual performance plan 2024/2025*. Government of KwaZulu-Natal.

Lam, T. Y. M., & Gale, K. (2023). A performance-driving model for public-sector construction framework procurement in England. *Built Environment Project and Asset Management*. https://doi.org/10.1108/bepam-02-2023-0043

Lester, A. (2014). Procurement. In A. Lester (Ed.), *Project management, planning and control* (6th ed., pp. 295–340). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-098324-0.00034-2

Liu, H. M., Hong, M. W., & Liu, S. Q. (2011). Analysis for construction project transaction methods decision based on fuzzy AHP. *2011 International Conference on Management and Service Science*, Wuhan, China. https://doi.org/10.1109/ICMSS.2011.5998202

Love, P. E. D., & Luo, H. (2018). Systems thinking in construction: Improving the productivity and performance of infrastructure projects. *Frontiers of Engineering Management*, *5*(3), 285–288. https://doi.org/10.15302/J-FEM-2018205

Master Builders KwaZulu-Natal. (2024). *Challenges facing contractors in KwaZulu-Natal*. Master Builders Association of KZN.

Mathonsi, M. D., & Thwala, W. D. (2012). Factors influencing the selection of procurement systems in the South African construction industry. *African Journal of Business Management*, *6*(10), 3583–3594. https://doi.org/10.5897/AJBM10.978

Maulanisa, N. F., Chumaidiyah, E., & Sriwana, I. K. (2024). A system dynamics modelling approach for improving engineering, procurement, and construction project performance: A case study. *Journal of Infrastructure, Policy and Development*. https://doi.org/10.24294/jipd.v8i11.8730

Moser, C. A., & Kalton, G. (2017). *Survey methods in social investigation* (2nd ed.). Routledge.

Ntuli, B., & Allopi, D. (2014). Impact of inadequate experience and skill on the construction sector in KwaZulu-Natal, South Africa. *Engineering, Technology & Applied Science Research*, *4*(4), 570–575. https://doi.org/10.48084/etasr.371

Osman, E. B. M. I., & Mohy, A. A. (2022). An impact of equipment selection on construction projects: Case study of a road project in Egypt. *Istraživanja i Projektovanja Za Privredu*, *20*(4), 1271–1281. https://doi.org/10.5937/jaes0-38963

Plunkett, S. (2021). Introduction to procurement methods in construction. In A. Speaight QC (Ed.), Architect's legal handbook: The law for architects (10th ed.). Routledge. https://doi.org/10.4324/9780429279546.

Ross-Smith, K., & Yearworth, M. (2011). Dynamics of operational procurement: Systems modelling for performance tracking and auditing. In *Proceedings of the 29th International Conference of the System Dynamics Society*. System Dynamics Society.

Rowlinson, S. (2022). Construction project procurement: A critical review. In R. Best & J. Meikle (Eds.), *Describing construction, industries, projects and firms* (1st ed., p. 26). Routledge. https://doi.org/10.4324/9781003155410

Rowlinson, S., & McDermott, P. (2005). *Procurement systems: A guide to best practice in construction*. Routledge. https://doi.org/10.4324/9780203982785

Ruparathna, R., & Hewage, K. (2015). Review of contemporary construction procurement practices. Journal of Management in Engineering, 31(3), Article 04014038. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000279.

Sahu, D., & Mohibullah. (2022). Effective criterion for equipment management in construction industry. In B. B. Das, C. P. Gomez, & B. G. Mohapatra (Eds.), *Recent developments in sustainable infrastructure (ICRDSI-2020)—Structure and construction management* (Vol. 221, pp. 185–199). Springer, Singapore. https://doi.org/10.1007/978-981-16-8433-3_17

Sakhare, V. D. (2024). Enhanced construction productivity by effective equipment management through fleet operations. *International Journal for Research in Applied Science and Engineering Technology*, *12*(4), 584–591. https://doi.org/10.22214/ijraset.2024.61889

Samee, K., & Pongpeng, J. (2016). Structural equation model for construction equipment selection and contractor competitive advantages. *KSCE Journal of Civil Engineering*, *20*(1), 77–89. https://doi.org/10.1007/S12205-015-0632-5

Soltanikarbaschi, N., & Hammad, A. (2023). An integrated AHP-TOPSIS methodology for selecting suitable project delivery method for construction projects. In S. Walbridge, R. M. N. Al-Hussaini, N. E. A. Zaki, C. M. L. S. T. S. K. Al-Ani, A. A. R. R. B. Abdeen, A. Al-Neshawy, & O. E. El-Badry (Eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021* (Vol. 247, pp. 599–609). Springer, Singapore. https://doi.org/10.1007/978-981-19-0968-9_48

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modelling for a complex world*. Irwin/McGraw-Hill.

Suratkon, A., Yunus, R., & Deraman, R. (2020). Characteristics of procurement methods in Malaysia – Comparing design bid build, design build and construction management. *International Journal of Sustainable Construction Engineering and Technology*, *11*(3), 1–11. https://doi.org/10.30880/IJSCET.2020.11.03.001

Trigunarsyah, B., & Al-Solaiman, S. (2015). Individual factors influence on client involvement: The case construction projects in Saudi Arabia. In *Proceedings of the 6th International Conference on Construction Engineering and Project Management*. Korean Institute of Construction Engineering and Management.

Uğur, L. O. (2017). Yapı makinesi satın alımında VIKOR çok kriterli karar verme yönteminin uygulanması [Implementation of VIKOR multi-criteria decision making method for construction machine purchase]. *Journal of Polytechnic*, *20*(4), 879–885. https://doi.org/10.2339/POLITEKNIK.369058

Watermeyer, R. (2022). Procurement and delivery management. In R. Watermeyer, *A guide to the NEC4 engineering and construction contract* (pp. 371–395). Edward Elgar Publishing. https://doi.org/10.4337/9781839108235.00025

Williams, B. (2005). *Systemic thinking and practice: Exploring knowledge from metaphor to model*. Routledge.

Windapo, A., Adediran, A., Rotimi, J. O. B., & Umeokafor, N. (2021). Construction project performance: The role of client knowledge and procurement systems. *Journal of Engineering, Design and Technology*, *19*(6), 1630–1655. https://doi.org/10.1108/JEDT-06-2020-0219

Zhong, Q., Tang, H., Chen, C. B., & Igor, M. (2022). A comprehensive appraisal of the factors impacting construction project delivery method selection: A systematic analysis. *Journal of Asian Architecture and Building Engineering*, *22*(2), 802–820. https://doi.org/10.1080/13467581.2022.2060983

.

JCBM (2025) 8(S1) 88-98

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Smart, but Not Spontaneous? Exploring the satisfaction Gap and drivers in Smart Lighting in Student Housing in Ghana

Iruka Chijindu Anugwo[1], Williams Miller Appau[2], Elvis Attakora-Amaniampong[3] and Frederick Simpeh[4]

[1]Department of Construction Management and Quantity Surveying / Faculty of Engineering and the Built Environment, Durban University of Technology, South Africa
[2&3]Department of Real Estate, Faculty of Planning and Land Management, Simon Diedon Dombo University of Business and Integrated Development Studies, Ghana
[4]Department of Construction and Wood Technology Education, Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development, Kumasi, Ghana

Received 15 October 2025; received in revised form 17 December 2025, 27 December 2025; accepted 28 December 2025
https://doi.org/10.15641/jcbm.8.S1.1934

Abstract

Smart lighting is emerging in student housing across Africa. This study assesses the drivers and satisfaction of smart lighting in university housing in Southern Ghana. The study used an embedded research method, including a survey of 334 student residents and interviews with 10 housing managers across five purpose-built student housing facilities at five selected public universities in Southern Ghana. The Relative Importance Index and thematic analysis were used as data analytical techniques. The findings reveal that accommodation needs primarily drove the adoption of smart lighting in student housing. The satisfaction levels of smart lighting were limited to lighting controls in lavatories, bedrooms, study areas, the kitchen, and common areas. However, dissatisfaction with lighting was associated with adjusting to the minimum light intensity and controlling artificial lighting. Technically, the limited influence of facilities management factors on smart lighting adoption poses a significant risk to energy sustainability if left unaddressed. Interviews reveal that students' lack of knowledge impacts their satisfaction with and usage of smart lighting systems. At a minimum, student housing managers and students would need education on smart lighting.

Keywords: Energy sustainability, smart lighting, sustainable design, student housing, Technology Acceptance Model

1. Introduction

In recent years, the widespread adoption of smart lighting in buildings has been hindered by several factors. Firstly, people do not have strong control over overall light quality; modest energy-saving returns complicate the justification for high initial investments, and user-responsive functionalities are limited (Füchtenhans et al., 2023). Despite these challenges, smart lighting continues to emerge as a promising multidisciplinary field, advancing not only energy conservation but also photobiological health, environmental psychology, and facilities management. In this context, smart lighting is widely regarded as a key element of sustainable building performance rather than purely a technological enhancement. Worldwide, smart lights can save up to 60 per cent of energy compared with conventional lighting systems in buildings (Papinutto et al., 2022). These systems increase productivity and improve light quality while offering dynamic adaptability. Despite this, technical importance, user satisfaction, perceived usability, and behavioural engagement remain underexplored, as the scholarly focus is still skewed disproportionately toward energy metrics, automation protocols, and return-on-investment calculations; these user-related contexts ultimately determine system performance in practice.

Smart building technologies address both surging energy costs and sustainability imperatives. They gained importance in Africa as economies grew. African Universities South of the Sahara consume much energy, and student residences are a key part of this demand (Appau et al., 2024). This has led institutions to implement green building policies to

[1] Corresponding Author
Email address: IrukaA@dut.ac.za

reduce carbon footprints and energy costs by integrating smart lighting technologies. Based on that, student housing has become a deliberate testing ground for smart lighting implementation in higher education across Africa. African nations are retrofitting student housing or designing smart student housing. These countries include South Africa, Egypt, Nigeria, and Ghana, and the features are occupancy-based controls, daylight-linked dimming, and remote monitoring systems (Gentile et al., 2022). In Ghana, interest in smart lighting arose from dissatisfaction with the legacy lighting infrastructure in student housing, as energy efficiency declined and utility costs rose (Appau et al., 2023).

Notwithstanding these developments, questions remain about how users experience and interact with lighting systems, particularly regarding satisfaction and effective use.

Although smart lighting is emerging in West Africa, particularly in university housing, empirical research has rarely examined user satisfaction and the factors that drive adoption. Most existing literature focuses on technical performance rather than user satisfaction and outcomes. How these findings hold in regions facing distinct economic constraints, energy policies, and environmental conditions remains unclear. At the same time, studies such as those by Soheilian et al. (2021) and Kwong (2020) suggest that user-controlled smart lighting systems positively influence indoor visual comfort and occupant well-being. Dong and Zhang (2021) link daylight exposure in student dormitories to improved mood, sleep quality, and cognitive performance. This work further supports the view that lighting is not merely a utility but a determinant of well-being. Recent studies also emphasise that emotional responses are significantly shaped by spatial ambience, thermal comfort, and lighting colour (Wei et al., 2023). However, these studies are mainly concentrated outside sub-Saharan Africa, underscoring the need for context-sensitive evaluations that account for regional and sociocultural variations, particularly in rapidly growing education hubs such as Ghana.

Although smart energy technologies are increasingly adopted in Ghanaian universities, an evident knowledge gap persists due to the limited user-oriented focus of existing studies. Smart lighting studies often assume a technologically literate population capable of interacting with complex systems. Nevertheless, findings from Appau et al. (2023) indicate that many Ghanaian student housing residents and facility managers are unaware of system features, such as automated dimming and daylight sensors. The smart lighting market is expected to grow at nearly 8 per cent globally by 2025 (Zissis, 2021). Hitherto, this projected growth has not been empirically assessed in terms of user satisfaction, behavioural engagement, or perceived usefulness in Ghanaian student housing. Even in more data-rich environments, such as Nigeria, residents may be dissatisfied with artificial lighting that is often poorly maintained, contributing to suboptimal residential experiences for students (Dennis et al., 2024). Nduka et al.'s (2021) research highlights health risks beyond those posed by inadequate indoor environmental quality, including sick building syndrome. These concerns raise questions about the expected benefits of smart lighting when user knowledge, training, and system adaptability are insufficient.

Against this background, this study addresses the limited understanding of user satisfaction and the drivers of smart lighting systems in Ghanaian student housing.

Having provided this background, the present study aims to assess residents' satisfaction levels and the drivers of smart lighting adoption in Ghanaian student housing. Student housing is a particularly suitable context due to its high occupancy levels, intensive energy use, and diverse user behaviours, making it an ideal context for examining the performance of smart lighting technologies.

Dormitory environments integrate institutional regulations, occupant behaviour, and spatial design, enabling examination of smart lighting under varying social and physical conditions. This contributes to knowledge by addressing an identified gap in the literature concerning user-centred evaluations of smart lighting in student housing within developing contexts.

First, it provides valuable feedback to facility managers and housing administrators on the features and configurations of smart lighting, ensuring alignment with user needs and preferences. This can guide procurement, retrofitting, and maintenance strategies that prove both cost-effective and user-friendly. Second, the study provides empirical grounding for sustainability efforts aimed at reducing the energy cost burden on universities and investors by identifying satisfaction levels and key drivers of adoption. These findings contribute to broader scholarly discussions on interior environments. In evaluating smart technologies, user-centric metrics are foregrounded. The study thereby addresses the increasing demand for research that balances technical performance with human experience, especially in areas that global scholarship has typically underrepresented.

2. Literature Review

2.1. Technology Acceptance Model

Davis (1989) developed the Technology Acceptance Model (TAM) as an extension of Ajzen's Theory of Reasoned Action. The model suggests that users' acceptance of technology is primarily influenced by two factors: perceived usefulness and perceived ease of use. Davis also emphasised that external variables, such as social influence, can significantly impact an individual's acceptance and adoption of new technology, within the context of bright lighting. The Technology Acceptance Model provides a suitable theoretical lens for understanding how students perceive lighting technologies and their perceived influence on satisfaction and usage behaviour. Recent advancements in applying the Technology Acceptance Model to smart buildings and energy technologies underscore its significance for understanding adoption decisions in residential and institutional contexts. Studies show that when users perceive smart systems as beneficial and easy to operate, adoption rates increase, even in shared living environments such as student housing. Although Technology Acceptance Model studies often assume a standard level of technological literacy among users, this assumption may not hold in all contexts, particularly in developing countries (Chen et al., 2017; Gerhardsson & Laike, 2021). This limitation highlights the need to contextualise TAM when examining smart lighting adoption in student housing.

2.2. Smart lighting systems adoption drivers in buildings

Smart lighting systems, as a subset of smart building technologies, integrate automation, sensing, and control mechanisms to optimise energy consumption and enhance operational efficiency. Studies have constantly identified energy efficiency and cost reduction as primary drivers of smart lighting adoption. For instance, Füchtenhans et al. (2023) and Kumar et al. (2021) report energy savings of up to 30.9 per cent, positioning smart lighting as a key strategy within sustainable building design frameworks.

Beyond energy considerations, managerial and organisational drivers also influence adoption decisions. Gøthesen et al. (2023) highlight perceived value and peer influence as factors shaping adoption, while Saleem et al. and Tekler et al. emphasise the role of real-time monitoring, automation, and personalised controls. In institutional contexts such as universities, facilities management priorities, maintenance budgeting, and security considerations also shape decision-making. However, these studies are conducted in commercial or general residential buildings, limiting their direct applicability to student housing environments, where shared spaces, high occupancy rates, and regulated usage patterns introduce additional complexity.

2.3. User satisfaction with Smart lighting and Daylighting

User satisfaction is a critical determinant of the long-term success of smart lighting systems, yet it is often examined inconsistently across studies. Existing studies often overlap discussions of daylighting, visual comfort, and energy savings, resulting in repetitive treatment of similar concepts. Studies by Soheilian et al. (2021) and Kwong (2020) demonstrate that user-controlled lighting systems improve visual comfort and perceived well-being. Similarly, Dong and Zhang (2021) link daylight exposure in student dormitories to improved mood, sleep quality, and cognitive performance.

Satisfaction levels, however, vary across spatial contexts. Bae et al. report dissatisfaction with artificial lighting and daylighting in dormitories, with implications for both comfort and academic performance. Conversely, Dong et al. (2022) report higher satisfaction in private dormitory rooms than in common areas. Osei-Poku et al. (2020) and Orman and Wojtkowiak (2022) find generally high satisfaction with lighting conditions in student housing in Ghana and Poland, respectively, illustrating the effects of regional, architectural, and cultural factors on user perceptions. Jakubiec et al. further note spatial variation in satisfaction, with students expressing greater contentment in bedrooms than in shared kitchens or communal areas.

Beyond perceptual outcomes, physiological and emotional responses to lighting are increasingly emphasised in the literature. Wei et al. (2023) show that lighting colour significantly affects emotional responses, while studies on daylight exposure highlight its impact on circadian rhythm and overall well-being. Despite this growing body of studies, user satisfaction is often treated as a secondary outcome rather than a central evaluative criterion.

2.4. Gaps in Sub-Saharan African Student Housing Research

Although research on smart lighting is expanding globally, significant gaps persist regarding Sub-Saharan African student housing. Most studies prioritise technological optimisation or energy performance metrics, with limited attention to user satisfaction, behavioural engagement, and contextual constraints. When user satisfaction is examined, findings are often drawn from data-rich or technologically advanced contexts, raising concerns about their transferability to developing regions.

In the African context, Appau et al. (2023) reveal limited awareness of smart lighting features among student housing residents and facility managers in Ghana. Similarly, Nduka et al. (2021) link inadequate lighting conditions to health risks, including symptoms of sick building syndrome, in Nigerian student hostels. These studies suggest that assumptions of ease of use and perceived usefulness may not align with lived experiences in student housing environments where training, maintenance capacity, and user literacy are limited. What emerges is a clear research gap: few studies integrate technology acceptance theory, adoption drivers, and user satisfaction within the specific context of Sub-Saharan African student housing. The intersection of high occupancy rates, energy cost pressures, and limited user knowledge remains underexplored. This gap underscores the need for empirical, user-centred investigations that examine not only why smart lighting is adopted, but also how it is experienced and utilised by students and housing managers in developing contexts, and how lighting influences well-being and academic engagement in student accommodations.

3. Research Methodology

The study employed embedded mixed-methods research. Thus, qualitative data were used to explain the quantitative findings. This method was used to assess students' satisfaction with smart lighting in student housing. The study adopted an embedded mixed-methods research design, where quantitative data collection preceded qualitative inquiry, and qualitative findings were used to explain and contextualise the quantitative results. This approach enabled a comprehensive understanding of students' satisfaction with smart lighting systems and the factors driving their adoption in student housing. The mixed-methods design is appropriate for examining both measurable satisfaction levels and underlying behavioural and managerial explanations. The questionnaire used in the quantitative phase was developed based on an extensive review of the literature on smart lighting, indoor environmental quality, and technology acceptance. The measurement indicators for smart lighting satisfaction (see Table 1) and adoption drivers (see Table 2) were adapted from validated constructs used in prior studies, including Appau et al. (2023), Bae et al. (2021), and Soheilian et al. (2021), to ensure content relevance. To establish content validity, the draft questionnaire was reviewed by two academics with expertise in

Table 1: Measurement of smart lighting systems satisfaction

Construct	Indicators	Mode of measurement
SLM1	End-users' control for indoor lighting (bedroom)	1=very dissatisfied, 5=very satisfied
SLM2	End-users' control for indoor lighting (study area)	1=very dissatisfied, 5=very satisfied
SLM3	End-users' control for indoor lighting (kitchen)	1=very dissatisfied, 5=very satisfied
SLM4	End-users' control for indoor lighting (lavatories)	1=very dissatisfied, 5=very satisfied
SLM5	End-users' control for indoor lighting (common areas)	1=very dissatisfied, 5=very satisfied
SLM6	End-users' artificial lighting power based on daylight levels	1=very dissatisfied, 5=very satisfied
SLM7	End-users' adjustment to minimum light intensity	1=very dissatisfied, 5=very satisfied
SML8	End-users' adjustment to control of natural lighting.	1=very dissatisfied, 5=very satisfied
SLM9	End-users' satisfaction with outdoor lighting illumination	1=very dissatisfied, 5=very satisfied

Source: authors' construct, 2024

Table 2: Drivers of the smart lighting adaptation

Variables	Indicators	Construct	Mode of measurement
Facilities management aspect	Student housing managers perceived the benefit of using smart lighting	ADD3	1=very low high influence, 5=very high influence
	Security and safety control	FMD1	1=very low high influence, 5=very high influence
	High energy cost	FMD2	1=very low high influence, 5=very high influence
	Maintenance budgeting	FMD3	1=very low high influence, 5=very high influence
	Availability of the smart lighting control manual	FMD4	1=very low high influence, 5=very high influence
Market-driven factors	Emergence of smart lighting in the student housing market	MDF1	1=very low high influence, 5=very high influence
	Student housing marketing appeal	MDF2	1=very low high influence, 5=very high influence
Accommodati on demand-driven factors	High occupancy	ADD1	1=very low high influence, 5=very high influence
	User knowledge of the smart lighting control device	ADD2	1=very low high influence, 5=very high influence

construction management and sustainable building systems, and by one facilities management practitioner with experience in student housing operations. Their feedback informed minor revisions to improve the clarity and relevance of the indicators. A pilot survey was subsequently conducted with 20 student housing residents who were not included in the final sample. The pilot test confirmed the clarity of questions and the average completion time.

Internal consistency reliability of the questionnaire items was assessed using Cronbach's alpha. Both the satisfaction scale and the adoption driver scale had alpha coefficients above the recommended threshold of 0.70, indicating acceptable reliability. These validation procedures ensured that the questionnaire items were both reliable and suitable for measuring the study constructs.

3.1. Sampling Technique and Sample Size

The study employed a two-stage sampling process to select respondents. First, the study conveniently sampled 5 out of 9 purpose-built on-campus university student housing in southern Ghana. The purpose was limited to a lack of accessibility to the remaining 4. Further, using the Yamane (1967) formula for sample size determination, a sample frame (N) of 2544, 50% of the population proportion, 5% margin of error Ɛ, and 95% confidence level:

$$n = \frac{N}{1 + N(e^2)}$$

$$n = \frac{2544}{\{1 + 2544(0.05^2)\}}$$

A sample of 331 was determined and used. Secondly, ten student housing managers were purposively selected for qualitative interviews, with two per selected housing facility. This dual perspective enabled triangulation between student experiences and managerial decision-making rationales. Qualitative data were collected through semi-structured interviews and analysed using a systematic thematic analysis procedure. Interview recordings were transcribed verbatim, after which open coding was conducted to identify recurring themes related to smart lighting use, satisfaction, and operational challenges. Codes with similar meanings were then grouped into broader categories, which informed the development of key themes. The coding process followed an iterative approach involving repeated reading of transcripts to refine and consolidate themes. Two researchers independently coded a subset of the transcripts; the coding outcomes were then compared, and discrepancies were discussed until consensus was reached, thereby strengthening interpretive reliability. This process enhanced the credibility and dependability of the qualitative findings. Data saturation was achieved when no new themes emerged from subsequent interviews. Final themes were reported using anonymised identifiers (e.g., SHM1, SHM2) to ensure confidentiality and clarity in data presentation.

3.2. Ethical consideration

Ethical approval for the study was obtained from the research committee of the study area and the Dean of Students' Office. These include: University of Cape coast (DHR/TDS/100/V.5/63), Kwame Nkrumah University of Science and Technology (KNUST/RO/GEN), University of Education, Winneba (R.252/RFU/80), University of Energy and Renewable Natural Resource (74 SF.1). All participants were informed about the purpose of the study, the voluntary nature of their participation, and their right to withdraw at any stage without penalty. Written informed consent was obtained from all respondents before administering questionnaires and conducting interviews. No personal identifiers were collected, and interview data were securely stored and accessed only by the research team.

4. Data analysis

The data analysis involved two stages. First, the study analysed the mean values of the indicators in Table 1 to ascertain satisfaction levels. Second, the study used the Relative Importance Index (RII) to derive the drivers of smart student housing. Here, ranks were assigned to the average levels of influence of adopting smart lighting in student housing. Where;

$$RII = \frac{\sum w}{A * N} = \frac{1n_1 + 2n_2 + 3n_n + 4n_4 + 5n_5}{5 * N}$$

$where\ (0 \leq RII \leq 1)$

Weight was assigned to each respondent, ranging from 1n (Very low influence), 2n (low influence), 3n (moderate influence), 4n (high influence), and 5n (very strong influence). A and N, on the other hand, show the highest weights and the largest numbers of respondents. Furthermore, the results were ranked in order of increasing importance. Moreover, the interviews were thematically analysed. Here, recorded data were transcribed into words and grouped into themes based on similar responses. Codes were assigned to student housing managers to ensure the ethical presentation of data. Finally, data saturation was achieved by gathering similar perspectives on the challenges of smart lighting usage from different student housing managers.

5. Findings

5.1. Descriptive results

The descriptive statistics in the study indicate a high response rate of 99.1%, with 331 of 334 student housing occupants participating. Males constituted a slight majority (53.8%) of respondents, and females 46.2%. Most participants were undergraduates (82.5%), while only 17.5% were postgraduates. This suggests that the studied group was skewed toward lower academic ranks (See Table 3).

The age distribution shows that most respondents were between 18 and 26 years old, with the 24-26 age group having the highest number (85). Afterwards, the numbers dropped to 21, 23 (79) and 18, 20 (73). Respondents aged 32 or older were very few, with only two participants aged 39 or older.

All age groups were represented in all five student housing facilities. Older students tend to live in Housing 2 and 3, with the majority of occupants being in the 24-26 age group. Older students were, by comparison, somewhat fewer in Housing 43 and Housing Preferences of the resident population, as well as in usage habits, implying that smart lighting strategies should prioritise the preferences of younger undergraduates, who dominate this area. Their impact on design decisions may be minimal given the relatively small number of older students. However, the age and academic-level distributions provide valuable context for understanding user satisfaction and adaptation to smart lighting systems in student housing environments.

5.2. Satisfaction with smart lighting adaptation

Table 4 presents the satisfaction of smart lighting systems in student housing. Table 4 reports five satisfactory levels of smart lighting system usage in Ghana. These include mean scores higher than the average mean scores (end-users' control for indoor lighting (bedroom), end-users' control for indoor lighting (study area), End-users' control for indoor lighting (kitchen), End-users' control for indoor lighting (lavatories), end-users' control for indoor lighting (common areas). On the flip side, student housing users expressed high dissatisfaction with end-

Table 3: Descriptive results

Age	**18-20**	**21-23**	**24-26**	**27-29**	**30-32**	**33-35**	**36-38**	**39+**
student housing 1	12	11	10	9	5	1	1	0
student housing 2	17	15	22	10	9	5	2	1
student housing 3	10	21	18	11	7	2	3	0
student housing 4	20	13	17	7	6	0	1	0
student housing 5	14	19	18	8	4	1	0	1
TOTAL	73	79	85	45	31	9	7	2
Gender								
Male	178	53.8						
Female	153	46.2						
TOTAL	331	100						
Levels in Class								
Undergraduate	273	82.5						
Postgraduate	58	17.5						
TOTAL	331	100						

Source: field data, 2024

Table 4: Satisfaction with smart lighting in student housing

Construct	**Indicators**	**Mean**	**Standard Deviation**
SML1	End-users' control for indoor lighting (bedroom)	3.6	0.8
SLM2	End-users' control for indoor lighting (study area)	3.6	1
SLM3	End-users' control for indoor lighting (kitchen)	3.5	1
SLM4	End-users' control for indoor lighting (lavatories)	3.7	0.7
SLM5	End-users' control for indoor lighting (common areas)	3.5	1.1
SLM6	Artificial lighting power based on daylight levels	2.8	1.2
SLM7	Adjustment to minimum light intensity	2.7	1.2
SLM8	Control of natural lighting	2.9	1.3
SML9	Satisfaction with outdoor lighting illumination	2.6	1.4

Source: field data, 2024

users' artificial lighting power based on daylight levels (end-users' adjustment to minimum light intensity, end-users' adjustment to control of natural lighting, and end-users' satisfaction with outdoor lighting). These are critical areas that student housing managers must address to ensure inclusive, sustainable lighting use in student housing. However, interviews with student housing managers highlighted a lack of knowledge as a critical barrier to students' use of smart lighting. According to student housing managers:

[….] It appears students are unaware of how these lights operate; maybe we need to educate them. Sometimes the need to instruct some of them to close their windows becomes apparent when the lights are on. This increases the energy cost to us [*sic*] (SHM8).

[….] "We may need a lighting system that automatically switches off when windows are opened." [*sic*] (SHM3).

[….] "Most students are unaware of how the lighting systems operate, which affects how effectively they use them." [*sic*] SHM1

[….] People should learn about smart lighting at orientation. Basic training is something that should occur during orientation. How many students switch on all of the lights in broad daylight? You will be surprised." [*sic*] SHM2

[….] We have had to remind some students about using natural lighting instead of keeping windows wide open with smart lights." [*sic*] (SHM5)

[….] Some students entirely ignore the sensors, along with becoming frustrated since they do not understand.", SHM4

[….] We only manage what is there. We think the student housing owners would need to make further enquiries before introducing these smart lighting systems in the housing, as they consider it a marketing strategy to increase student numbers in the hostel [*sic*] (SHM8).

[….] I think that because some student housing managers have started using it, my boss has also introduced it here. For me, it is a good idea provided it will serve the purpose of the students [*sic*] (SHM8).

[….] We installed the system mainly as an action to cut down on our electricity bills, not for the sake of technology.", SHM16

[….] Some landlords use smart lighting as a marketing tool instead of caring about comfort or sustainability." SHM17 states

.

[….] Energy consumption rises when many students attend. "That is why we need smart lighting. SHM18 says usage regulation involves smart lighting.

5.3. Drivers of smart lighting adaptation in student housing

Table 5 presents a detailed breakdown of the critical factors influencing the adoption of smart lighting in student housing in Ghana. The data, analysed using the Relative Importance Index (RII), are grouped into three major categories: Accommodation Demand-Driven (ADD), Facilities Management-Driven (FMD), and Market-Driven Factors (MDF). The results reveal that accommodation-driven and facilities management considerations significantly outweigh market-related influences in determining the adoption of smart lighting systems.

The most influential factor, ranked first, is ADD3 – student housing managers' perceived benefit of using smart lighting, with an RII value of 0.82. This

Table 5: Drivers of smart lighting adaptation in student housing

Indicators	1	2	3	4	5	Total (H)	Total Respondent (I)	HR (J)	I*J (K)	H/K	RANK
ADD1	1	2	0	12	15	30	10	5	50	0.6	3
ADD2	1	6	4	8	5	24	10	5	50	0.47	5
ADD3	0	2	3	16	20	41	10	5	50	0.82	1
FMD1	4	4	6	4	5	23	10	5	50	0.46	6
FMD2	1	4	9	8	10	32	10	5	50	0.64	2
FMD3	2	10	3	4	5	24	10	5	50	0.48	4
FMD4	3	8	6	0	5	22	10	5	50	0.44	7
MDF1	3	10	3	0	0	16	10	5	50	0.32	8
MDF2	2	10	6	4	0	22	10	5	50	0.44	7

Source: field data, 2024

(Note: Total weighted score for each indicator, calculated as the sum of the product of each rating scale value and its frequency, I=Total number of respondents, J=Highest weight on the Likert scale (i.e., 5), I × J (K)=Maximum possible score for each indicator, H/K: Relative Importance Index (RII), representing the relative influence of each factor.

Another group of student housing managers expressed that their motivation and operational satisfaction:

underscores that managers prioritise the long-term operational advantages of smart lighting, particularly its potential to lower energy consumption, reduce utility costs, and enhance the overall efficiency of student housing operations. Following this, ADD1, with a high occupancy rate, ranks third with an RII of 0.60. This reflects the concern that higher numbers of student occupants lead to greater energy demands, making smart lighting a viable strategy for controlling excessive usage and maintaining cost efficiency. ADD2, which represents user knowledge of smart lighting control devices, ranks fifth with an RII of 0.47. Although this is moderately influential, it suggests that students' ability to use smart systems effectively is important but not a central driver of decision-making.

From a facilities management standpoint, FMD2 – high energy cost – ranks second overall with an RII of 0.64. This suggests that rising electricity costs are a significant motivator for the adoption of energy-saving technologies, such as smart lighting. Managers view smart systems as essential tools to offset the financial burden of rising utility rates. FMD3, which addresses maintenance budgeting, ranks fourth at 0.48. Although not as dominant as perceived benefits or energy costs, the desire to reduce maintenance expenditure still contributes to the adoption rationale. FMD1 – security and safety control – ranks sixth with an RII of 0.46, suggesting that safety concerns are acknowledged but are not primary drivers. FMD4 – availability of smart lighting control manuals – and MDF2 – marketing appeal of smart student housing – are tied in seventh position with an RII of 0.44. This suggests that providing users with instructions or utilising smart lighting as a marketing tool has a relatively low influence on decision-making.

The least influential factor, MDF1 – emergence of smart lighting in the student housing market – ranks eighth with an RII of 0.32. This shows that broader market trends or technological novelty are not strong motivators for adoption among student housing managers. Instead, decisions are shaped more by internal operational concerns than by external industry developments.

6. Discussion

The findings of this study contribute to the growing body of research on smart lighting adoption and satisfaction by providing context-specific empirical evidence from Ghanaian student housing. While the results broadly align with global smart lighting literature, they also reveal significant contextual deviations that extend the explanatory power of the Technology Acceptance Model (TAM) when applied to shared residential environments in developing regions. Consistent with TAM, the study confirms that perceived usefulness is the dominant determinant of smart lighting adoption, as evidenced by the high ranking of student housing managers' perceived benefits of smart lighting (ADD3). This supports Davis's (1989) assertion that perceived usefulness exerts a more substantial influence on adoption than perceived ease of use. Similar findings have been reported in smart building studies by Füchtenhans et al. (2023) and Gøthesen et al. (2023), where energy cost reduction and operational efficiency drive adoption decisions. In the Ghanaian context, perceived usefulness is primarily framed in economic and operational terms rather than technological novelty, reflecting the budgetary constraints faced by student housing operators.

However, the study extends TAM by demonstrating that perceived usefulness alone does not guarantee user satisfaction or effective system utilisation. Although smart lighting was adopted for its perceived benefits, satisfaction levels varied across lighting functions. Users reported satisfaction with lighting control in bedrooms, study areas, kitchens, and common areas, but dissatisfaction with daylight-linked dimming, minimum light-intensity adjustment, and outdoor lighting. These findings indicate a disconnect between adoption motivations (managerial-level usefulness) and user-level experiential outcomes, a relationship that the original TAM framework does not fully explain.

User knowledge emerges from the findings as a critical mediating variable between perceived usefulness and actual system satisfaction. Interview evidence indicates that many students lack awareness of how smart lighting systems interact with natural light and sensors. This mediating role of user knowledge helps explain why systems perceived as applicable by managers may still produce dissatisfaction among end users. In this sense, user knowledge mediates the relationship between perceived usefulness and actual use outcomes, thereby refining TAM's assumption that perceived usefulness directly translates into positive user behaviour.

In addition, a high occupancy rate serves as a contextual moderating variable that influences adoption decisions. The RII analysis shows that high occupancy (ADD1) strongly influences smart lighting adoption, as increased student density intensifies energy demand and operational pressures. This finding extends TAM by introducing an environmental–institutional moderator, where adoption is shaped not only by individual perceptions but also by occupancy-driven energy stress. Such a variable is absent mainly from conventional TAM applications, which focus on individual-level decision-making rather than institutional constraints.

The relatively low influence of market-driven factors further reinforces the context-specific nature of smart lighting adoption in Ghanaian student housing. Unlike Saleem et al. (2023), who found that innovation trends and technological appeal influenced adoption, this study shows that marketing appeal and market emergence play minimal roles in adoption. This suggests that external variables within TAM operate differently in resource-constrained environments, where economic survival and operational efficiency take precedence over reputational or branding considerations.

Importantly, speculative claims regarding safety, learning performance, or long-term behavioural change have been avoided in this discussion, as the study did not directly measure these outcomes. While prior studies link lighting conditions to academic performance and well-being, the present findings are limited to satisfaction levels, adoption drivers, and user knowledge gaps. Interpretations have therefore been restricted to variables empirically examined in the study, ensuring analytical rigour.

This study contributes to theory by contextualising and modestly extending TAM rather than replacing it. The findings suggest that TAM remains a useful baseline for understanding smart lighting adoption. Still, its predictive strength improves when supplemented with mediating variables (user knowledge) and moderating contextual factors (occupancy pressure and energy cost constraints). In shared residential environments such as student housing, adoption decisions are institutionally driven, while satisfaction outcomes depend heavily on user capacity to interact meaningfully with installed technologies.

7. Theoretical and practical implications

This study contributes both theoretically and empirically to the Technology Acceptance Model (TAM) by contextualising it within the context of sustainable infrastructure, specifically brilliant lighting in student housing in Ghana. This study improves the TAM, which typically centres on perceived usefulness and perceived ease of use, by introducing context-specific external factors such as occupancy rate, energy cost concerns, and facility management priorities. These drivers strongly influence technology adoption decisions, although they fall outside the original TAM framework. By managing an environment and designing infrastructure within TAM's predictive framework, the study employs a model for sustainability-oriented decisions in the built environment. For multiple stakeholders, the findings have practical implications. Firstly, university student housing administrators must educate all students to ensure they understand and use smart lighting systems properly. The study reveals that students' limited knowledge leads to inefficient use and dissatisfaction. During orientation, train individuals in a structured manner and post informational signs throughout housing facilities.

Secondly, technology building suppliers and contractors should be held fully accountable. They should integrate automated features, such as daylight sensors and adaptive dimming functions, into their lighting systems. Reported dissatisfaction includes a need to adjust lighting due to varying daylight intensities. Therefore, automation is needed to reduce dependence on manual labour.

Smart lighting integration is encouraged for university finance and energy management units. These units should incorporate smart lighting as part of their broader energy-saving strategies, thirdly. Given the emergence of high energy costs as a dominant driver, leveraging smart lighting to achieve measurable reductions in energy expenditure must be a core component of operational planning. Fourth, facilities managers and campus estate officers must consider incorporating smart lighting systems into all planning and procurement processes. They must also include them within the post-occupancy evaluation of all student housing infrastructure. These systems are designed as components of sustainable building performance. They should not be viewed simply as add-ons.

Finally, student housing design consultants and architects are responsible for ensuring uniform lighting standards across all spatial areas. Satisfaction is high in bedrooms and study areas, but relatively low in kitchens and outdoor spaces, according to the study. This spatial inconsistency suggests that design standards should ensure lighting quality and functionality across all zones.

8. Conclusions and recommendations

This study examined user satisfaction and the key drivers of smart lighting adoption in student housing in Ghana, using an embedded mixed-methods approach. The findings indicate that the adoption of smart lighting in student housing is primarily driven by perceived operational benefits, high energy costs, and high occupancy levels, whereas market-driven factors play a limited role. Regarding satisfaction, users reported positive experiences with lighting control in bedrooms, study areas, kitchens, lavatories, and common areas. Still, they expressed dissatisfaction with daylight-linked dimming, adjustment to minimum light intensity, control of natural lighting, and outdoor lighting illumination.

Given the perceived benefits of adopting smart lighting, student housing managers must invest in high-quality smart lighting to realise anticipated energy efficiency and cost savings. Additionally, student housing managers must invest in smart lighting that automatically turns off when students open windows to allow natural light. However, student housing users need to be educated on how to adjust smart lighting to complement natural lighting and promote energy efficiency. Managing outdoor lighting levels will require increased use of high-voltage smart lighting, particularly in student housing that utilises solar panels for outdoor lighting. Future studies should include experimental evaluation of training interventions and longitudinal tracking of actual energy consumption versus perceived benefits of smart lighting in student housing.

References

Appau, W.M., Attakora-Amaniampong, E. and Anugwo, I.C. (2024). Indoor environmental quality and energy use intensity: an empirical post-occupancy evaluation test of on-campus university student housing in Ghana. Property Management. 42(3), pp. 333-352. https://doi.org/10.1108/PM-07-2023-0058

Appau, W.M., Anugwo, I. C., Okorie, N. V., and Attakora-Amaniampong, E. Smart Energy Solution Literacy among Student Housing Managers: Perspective of Awareness and Challenges in Ghana. (2023). In J. N. Mojekwu et al. (Eds.): Sustainable Education and Development, Springer Nature. PP 53-67

Bae, S., Martin, C. S., & Asojo, A. O. (2021). Higher education students' indoor environmental quality satisfaction benchmark. *Building Research & Information*, *49*(6), 679-694.

Chen, C. F., Xu, X., & Arpan, L. (2017). Between the technology acceptance model and sustainable energy technology acceptance model: Investigating smart meter acceptance in the United States. Energy research & social science, 25, 93-104.

Davis, F.D., Bagozzi, R.P. and Warshaw, P.R. (1989), "User acceptance of computer technology: a comparison of two theoretical models", Management Science, 35(8), pp. 982-1003

Dennis, A., Daramola, O., Anjorin, O. G., & Olushola, D. O. (2024). Assessing Occupant Satisfaction in Mary Hall Residence at Caleb University, Lagos. *African Journal of Environmental Sciences and Renewable Energy*, *17*(1), 86-97.

Dong, Z., Zhao, K., Ren, M., Ge, J., & Chan, I. Y. (2022). The impact of space design on occupants' satisfaction with indoor environment in university dormitories. *Building and Environment*, *218*, 109143.

Dong, Y., & Zhang, X. (2021). Study on the effect of awakening daylight in dormitories on morning alertness, mood, fatigue and sleep quality of college students. *Building and Environment*, *203*, 108060.

Füchtenhans, M., Glock, C. H., Grosse, E. H., & Zanoni, S. (2023). Using smart lighting systems to reduce energy costs in warehouses: A simulation study. *International Journal of Logistics Research and Applications*, *26*(1), 77-95.

Gerhardsson, K. M., & Laike, T. (2021). User acceptance of a personalised home lighting system based on wearable technology. Applied Ergonomics, 96, 103480.

Gentile, N., Lee, E. S., Osterhaus, W., Altomonte, S., Amorim, C. N. D., Ciampi, G., ... & Sibilio, S. (2022). Evaluation of integrated daylighting and electric lighting design projects: Lessons learned from international case studies. *Energy and Buildings*, *268*, 112191.

Gøthesen, S., Haddara, M., & Kumar, K. N. (2023). Empowering homes with intelligence: An investigation of smart home technology adoption and usage. *Internet of Things*, *24*, 100944.

He, W., & Zeng, N. (2025). The Relationship Between University Dormitory Environmental Factors and Students' Informal Learning Experiences: A Case Study of Three Universities in Guangdong Province. *Buildings*, *15*(14), 2518.

Jakubiec, J. A., Srisamranrungruang, T., Kong, Z., Quek, G., & Talami, R. (2019). Subjective and measured evidence for residential lighting metrics in the tropics. *Building Simulation, Rome, Italy*.

Kumar, A., Sharma, S., Goyal, N., Singh, A., Cheng, X., & Singh, P. (2021). Secure and energy-efficient smart building architecture with emerging technology IoT. *Computer Communications*, *176*, 207-217.

Kwong, Q. J. (2020). Light level, visual comfort and lighting energy savings potential in a green-certified high-rise building. *Journal of Building Engineering*, *29*, 101198.

Nduka, D. O., Oyeyemi, K. D., Olofinnade, O. M., Ede, A. N., & Worgwu, C. (2021). Relationship between indoor environmental quality and sick building syndrome: a case study of selected students' hostels in Southwestern Nigeria. *Cogent Social Sciences*, *7*(1), 1980280

Osei-Poku, G., Braimah, A., & Clegg, R. (2020). Comparative assessment of user-satisfaction with on-campus residential accommodation at Takoradi Technical University, Ghana. *Journal of Building Performance, ISSN 11*(1), 2020.

Orman, Ł. J., & Wojtkowiak, J. (2022). Case study of thermal comfort, lighting conditions and productivity at two classrooms of Poznań University of Technology. Structure and Environment, 14(2).

Papinutto, M., Boghetti, R., Colombo, M., Basurto, C., Reutter, K., Lalanne, D., ... & Nembrini, J. (2022). Saving energy by maximising daylight and minimising the impact on occupants: An automatic lighting system approach. *Energy and Buildings*, *268*, 112176.

Saleem, M. U., Shakir, M., Usman, M. R., Bajwa, M. H. T., Shabbir, N., Shams Ghahfarokhi, P., & Daniel, K. (2023). Integrating smart energy management systems with the Internet of Things and cloud computing for efficient demand side management in smart grids. *Energies*, *16*(12), 4835.

Soheilian, M., Fischl, G., & Aries, M. (2021). Smart lighting application for energy saving and user well-being in the residential environment. *Sustainability*, *13*(11), 6198.

Tekler, Z. D., Low, R., Yuen, C., & Blessing, L. (2022). Plug-Mate: An IoT-based occupancy-driven plug load management system in smart buildings. *Building and Environment*, *223*, 109472.

Wei, Y., Zhang, Y., Wang, Y., & Liu, C. (2023). A study of the emotional impact of interior lighting color in rural bed and breakfast space design. *Buildings*, *13*(10), 2537

Zissis, G., Bertoldi, P., & Serrenho, T. (2021). Update on the Status of the LED Lighting World Market since 2018. *Publications Office of the European Union: Luxembourg*.

JCBM (2025) 8(S1) 99-110

University of Cape Town
Journal of Construction Business and Management
http://journals.uct.ac.za/index.php/jcbm

Integrating sustainable materials into construction: A review of Zimbabwe's Model building by-laws

Cynthia Moyo[1], Tirivavi Moyo[2] and Mable Vongai Mudombo[3]

1Department of Construction Management, Nelson Mandela University, Gqeberha, South Africa
[2]Department of Quantity Surveying, Nelson Mandela University, Gqeberha, South Africa
[3]Faculty of the Built Environment, National University of Science and Technology, Bulawayo, Zimbabwe

Received 10 October 2025; received in revised form 30 November 2025, 25 December 2025; accepted 28 December 2025
https://doi.org/10.15641/jcbm.8.S1.1936

Abstract

Environmental challenges associated with the use of traditional construction materials are widespread in Zimbabwe. Despite the availability of sustainable construction materials, the failure to adopt the Model Buildings by-law of 1977 has stalled the promotion of strategic interventions. Hence, the study identified pertinent modifications to the Model building by-laws that could enable the utilisation of sustainable construction materials—the interpretivist philosophy employed semi-structured online interviews. Purposive sampling was used to solicit views from sixteen (16) construction professionals, academics, and relevant local government officials with experience in sustainable construction. The generation of modern by-laws with relevant, sustainable material specifications, design-related modifications, and the adoption of green building principles or methodologies were the major themes identified. A comprehensive stakeholder engagement was recommended to ensure that any modifications are practical and implementable. Using sustainable construction materials requires a policy intervention incorporating a comprehensive stakeholder support framework from manufacture to material disposal. The paper highlights the necessary changes to the model-building by-laws (MBBLs) to integrate sustainable construction material utilisation in Zimbabwe. This is valuable to all stakeholders in the construction industry as it aligns with the Sustainable Development Goals of climate action and responsible production and consumption. The main limitation was the exclusive use of a key-informant qualitative design rather than end users. However, the exploratory nature of the study supported the approach.

Keywords: Building regulations, Model building by-laws, Sustainable construction materials, Zimbabwe.

1. Introduction

According to the United Nations Sustainable Development Agenda (2020), sustainable development is an advancement that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations, 2020). In addition, at the core of sustainability are three elements: economic growth, social inclusion, and environmental protection. Hence, sustainability aims to ensure that every development enables the availability of resources for everyone, meets human rights and basic needs, and consumes natural resources at a rate that allows them to replenish themselves, guaranteeing balanced ecosystems. Sustainable construction is a subset of sustainable development concentrating on managing a healthy built environment based on resource-efficient and ecological principles (Baloi, 2003). The built environment shapes the context of most human activities and accounts for a significant share of any economy; moreover, construction leaves behind environmental and carbon footprints (Brennan, 2015). The construction industry has an enormous impact on the economy, environment, and health of a nation, as it is the leading universal user of materials and one of the significant primary energy-consuming sectors, contributing significantly to atmospheric emissions (Demir & Dogan, 2020). However, due to urbanisation and globalisation, environmental deterioration and resource depletion have increased, leading to the need to alleviate resource depletion (Mathiyazhagan et al., 2019). In fact, the construction sector continues to be one of the largest global consumers of natural resources, utilising an estimated 40% of global

[1] Corresponding Author
Email address: cynthiamhungu@gmail.com

extraction of non-metallic minerals (such as sand, gravel and stone) and around 25% of global timber production (Kibert, 2022). Moreover, the heightened awareness of global environmental threats, such as climate change, has led to greater interest in low-carbon embodied materials for sustainable building (Agyekum et al., 2022). Sustainable construction has been observed as the solution, requiring sustainable materials. This is because sustainable construction materials have zero environmental impact and are reusable and recyclable (Onyegiri & Ugochukwu, 2016), resulting in benefits across the economic, social, and environmental dimensions of sustainability (Eze et al., 2023).

Despite over 30 years of discourse on sustainability, the adoption of sustainable construction materials to achieve a sustainable built environment has lagged, and developing countries, such as Zimbabwe, need support in this regard (Moyo et al., 2024). Chari and Chiriseri (2014) noted that sustainability principles must be factored into procurement decisions within both private and public entities in Zimbabwe. According to the Global Climate Risk Index (2021), Zimbabwe was among the world's ten most affected countries by climate change in 2019 (United Nations Climate Technology Centre and Network (CTCN), 2022), a potential motivator for enhancing sustainable construction practices. As a result, Altuma and Ghasemlounia (2021) state that, as the construction industry continues to grow, it is essential to use innovative technologies and creative approaches to select construction materials to sustain available resources. According to Eze et al. (2023), more studies are required on the adoption of sustainable construction materials in developing countries in Africa, including Nigeria. Therefore, this study suggested modifications to the Model Building by-laws to integrate sustainable utilisation of construction materials in Zimbabwe. The concomitant objective was to identify and prioritise modifications to the 1977 MBBLs that would enable the adoption of sustainable construction materials in Zimbabwe. Sustainable construction materials are environmentally friendly and minimise environmental challenges such as ecosystem imbalances, pollution, greenhouse gas (GHG) emissions, and other issues arising from conventional building materials, which are hostile to ecosystems, unsustainable, and harmful to the environment (Eze et al., 2021). The sustainable construction materials proffered by Eze et al. (2021) are grounded in the cradle-to-cradle model (Braungart & McDonough, 2009) and the diffusion of innovation Theory (Wani & Ali, 2015), as they promote human safety through innovation-enhancing policies.

It is critical for policymakers to build a robust, sustainable economy (Mathiyazhagan et al., 2019). The following sections review the theoretical framework and related literature. Thereafter, the methodology is reported and justified. The results are presented and discussed. Finally, the conclusions and recommendations are outlined.

2. Literature Review

This section focused on the study's theoretical framework and the role of MBBLs in incorporating sustainable construction material utilisation, as proffered by previous studies.

2.1. Theoretical framework

The adoption of sustainable materials depends on multiple factors. The research used a fusion of two theories to address impacts at individual, organisational, and inter-organisational levels, as applied by Tran et al. (2020). The two theories are the cradle-to-cradle model (Braungart & McDonough, 2009), which emphasises the use of building materials that promote safe, healthy environments for all humans, and diffusion of innovation theory (DOI) (Wani & Ali, 2015). The cradle-to-grave model promotes circular construction practices that select materials that cause the least environmental harm. Wani and Ali (2015) state that the Diffusion of Innovation Theory (DOI) is grounded in well-established sociological, psychological, and communication theories. In addition, diffusion is the process by which innovation is communicated over time through specific channels among members of a social group. Further, the construction industry differs from other industries in that innovation depends upon adoption or implementation and problem-solving based on organisational learning.

Four critical aspects make up DOI: innovation, communication channels, time, and social systems, through a five-stage innovation process comprising knowledge, persuasion, decision, implementation, and confirmation (Tran et al., 2020). Unfortunately, the project-based nature of the industry, short-term relationships, and decentralised organisational structures do not foster learning, meaning the adoption of innovation is evaluated in the same context as individuals rather than through scientific studies (Wani and Ali, 2015). Tran et al. (2020) note that under the DOI, external social and political contexts are critical factors influencing the adoption of innovation, including sustainable materials. To achieve sustainable building by-laws, there must be a cooperative effort amongst interrelated units, including developers, designers, contractors, subcontractors, suppliers, government, and users or clients.

The contributions of the theories to the adoption of sustainable construction materials are expanded in the next section. The importance of materials that reduce harm to humans and the environment is promoted, with a focus on how regulatory frameworks like the MBBLs can be used to integrate and promote their inclusion.

2.2. Modern building by-laws for the adoption of sustainable construction materials

Among the planning tools, including development plans, town planning schemes, and building by-laws, the building by-laws are the most effective in shaping the built environment and achieving sustainable development (Chirisa, 2014). Regulatory barriers that prevent the adoption of sustainable materials are also prevalent in developed countries, resulting from unsuitable and non-comprehensive by-laws (Hoxha & Lecaj, 2024). Although Mogaji et al. (2024b) identified the importance of government regulations in advancing the adoption of innovative building materials, the authors did not offer any replicable implementation model. As such, including sustainability in the by-laws without specifying conformity guidelines for sustainable materials does not motivate their adoption in construction practice but ends at an experimental level. In Zimbabwe, the Ministry of Local Government and Housing published the Model Building By-laws in 1977 under the Urban Councils Act, Chapter 214, section 183, and Section 83A of the Rural Councils Act (Chirisa, 2014). The document covers structural design, foundations, masonry, walling, and construction of miscellaneous materials. These include that building by-laws often contain clauses that do not enable the adoption and implementation of sustainable construction materials. In addition, there is also a general need for more regulatory testing and inspection requirements for sustainable construction to ensure law enforcement. Also, green labelling of building materials, green building technologies and sustainable buildings where they have been applied is critical.

Including labelling in the drafting of by-laws will make it easier for consumers to identify sustainable products and technologies. Noted deficiencies in the existing Model building by-laws include the absence of sustainable construction materials, the rigidity of the by-laws, a lack of alternatives to traditional materials, insufficient information on the sustainability of included materials, and inadequate references to sustainable design. Chirisa (2014) identified critical inadequacies in the current model-building by-laws. Further literature on the use of sustainable construction materials includes Zami (2014), Mafuku (2019), and Kativu et al. (2023). Zami (2014) bemoans the lack of adequate regulatory mechanisms to drive the adoption of stabilised earth construction to alleviate the housing crisis. The author emphasises a lack of drive to implement the successfully tested stabilised earth construction for urban houses. Aligning with this, Mafuku (2019) laments the slow adoption of green construction in Zimbabwe, which promotes the use of green construction materials. In this regard, Kativu et al. (2023) highlight the contribution of poor regulatory frameworks to inadequate construction material waste management. This is particularly significant, as it exposes the extent of existing construction material waste management and the need to utilise sustainable construction materials.

However, these anomalies are not peculiar to Zimbabwe. In Kosovo, it was noted that spatial planning laws were silent on goals such as sustainable design, cities, infrastructure, and construction to ensure rational economic use of land (Hoxha & Lecaj, 2024). This is similar to what Chirisa (2014) identified. Fini and Akbarnezhad (2019) support the promotion of responsible procurement of materials by considering their economic, environmental and social impacts. However, this can only be achieved if the necessary technical support systems have been established and operationalised. Unfortunately, the Public Procurement and Disposal of Public Assets Act [Cap 22:2] fails to achieve this objective (Sakutemba et al., 2024). In addition, Nasier (2021) argues that the major constraint is that the selection of sustainable construction material must be practical, specific and aligned with budget needs. Again, practicality speaks to availability, which the construction material supply value chain fails to ensure (Sakutemba et al., 2024). Hoxha & Lecaj (2024) highlight constraints concerning by-laws that align with Mogaji et al. (2024a)'s findings regarding a lack of awareness and knowledge, as well as a lack of end-user involvement. As such, Kylili (2017) advocates increased use of sustainable construction materials by promoting well-supported policies. This also means that materials are to be labelled not only on their structural or mechanical performance but also on their energy performance, carbon footprint, health effects, thermal performance, indoor comfort, and environmental effects. To ensure the enforcement of labelled materials in practice, by-laws should include tax levies and provide end-user information on labelled materials (Hoxha & Lecaj, 2024). Smith (2015) notes that various international rating systems, such as BREEAM (UK and Europe), LEED (USA), GBAS (China), DGNB (Germany), and Green Star Australia, have been developed to promote sustainable construction. In addition, to promote localised sustainability standards, the Ministry of New and Renewable Energy established the Green Rating for Integrated Habitat Assessment (GRIHA) as the mandatory certification system for government buildings (Smith, 2015). In India, the Model Building By-laws (2016) require buildings on plots over 100 m2 to comply with green norms using LEED and GRIHA, emphasising renewable, prefabricated, or recycled materials and encouraging the use of locally sourced resources to reduce transport impacts (Singh and Kumar, 2023). The reviewed literature examines the model by-laws' exclusion of sustainable construction materials in developed and developing countries, as well as the contributions of scholars from those contexts.

3. Research Methodology

This study adopted an interpretive philosophy and a qualitative research design to review the model-building by-laws for incorporating sustainable construction material utilisation in Zimbabwe, similar to Hoxha and Lecaj's (2024) study. This philosophy is focused on understanding the meanings people attach to their experiences, rather than measuring or predicting phenomena. It assumes that reality is socially constructed, that knowledge is co-created between researchers and participants, and that values and context influence all interpretations (Lee et al., 2023; Crowther & Thomson, 2020). The collected data were inductively utilised to build themes and patterns (Saunders et al., 2016). A qualitative methodological approach was used to collect data through narrative inquiry, aligned with participants' opinions and experiences (Leedy and Ormrod, 2013). A cross-sectional time horizon is selected when answering a question or solving a problem that requires collecting data within a specific time frame. Time horizons determine whether the study is a snapshot in time or a series of event representations over a given period (Saunders et al., 2016).

As supported by Babbie and Mouton (2015), this empirical research was grounded in the collection of primary data through semi-structured online interviews. The online interviews lasted no more than 60 minutes and were recorded after participants provided consent. An outsourced professional transcribed the audio, and member checking was conducted to confirm the data's validity. The interview guide consisted of demographic questions and questions that asked participants to offer their opinions on critical ways to incorporate sustainable construction material utilisation.

The researcher applied purposive sampling (Saunders et al., 2016) to solicit views from an equal representation of at most five local authorities or government officials, five researchers, and five green building or five construction professionals, as these were individuals with known or demonstrable experience and expertise in the area, spanning at least 3 years. Participants were sought from across the country through targeted outreach to universities, organisations, and professionals who had participated in sustainable construction-related research and projects. This information is available on the universities' or organisations' websites and local authority registers. The basics of this technique include all opinions or views; therefore, representation was not about proportions but about views or ideas. The critical aspect of this technique is to engage multiple consultants rather than a single consultant to achieve diversity through concept mapping. According to Saunders et al (2016) and Hennink et al. (2017), a minimum of four and a maximum of 24 interviews are deemed sufficient for an exploratory study. In addition, interviews must be done until saturation is achieved. While the study targeted at least five interviewees, interviews were conducted till saturation was achieved, that is, when no additional information on the objective was forthcoming. To achieve this, 20 potential interviewees were requested to participate. Interviews were conducted over 90 days at different times and in different settings, with interviewees from various backgrounds, thereby increasing the reliability of the results. The reliability of the qualitative data was enhanced using ATLAS.ti (version 25.0.1) and two independent coders, ensuring consistency and transparency in data interpretation. As Saunders et al. (2016) emphasise, reliability in qualitative data analysis depends on coders adhering to clear, replicable coding guidelines and working independently. In addition, the percentage of agreement was 95%, which was >80%, and this was accurate for a few categories (Bolognesi, Pilgram & Van der Heerik, 2016). Disagreements (5%) were minimal and resolved through coders' consensus and reference to the existing literature.

Data analysis was done using thematic analysis, a systematic qualitative method for identifying, organising, and offering insight into themes or meaning patterns across a dataset. This approach enables researchers to capture both explicit and underlying themes that reflect participants' experiences and perspectives (Braun and Clarke, 2022). The process involved familiarising with data associated with modifications to the Model building by-laws, coding interesting interventions of the data, generating a category from the codes and a theme map, defining themes, and finally producing the report relating to the research question and literature (Vaismoradi, 2013). Codes were developed deductively from existing literature. The codes were used to build categories by considering their relationships. The same categories were then used to build the themes, which were agreed upon by the coders.

To promote the research's aims in knowledge, truth, and error avoidance by prohibiting fabrication, falsification, or misrepresentation of research data, ethical considerations were implemented in the study, as supported by Resnik (2020). Ethics are norms for conduct that distinguish between acceptable and unacceptable behaviour (Saunders et al., 2016). Ethics approval was sought and approval granted for a low-risk study by the Department of Construction Management at the National University of Science and Technology in Zimbabwe. The researcher was responsible for protecting the respondents' rights during the research. Permission to conduct research was sought from respondents before engaging them. The researcher informed respondents before the interviews of how the information would be used. Ethical guidelines regarding informed consent, confidentiality, and anonymity were adhered to. Respondents were informed of the study's purpose and invited to participate, with no one required to participate under duress. Scientific honesty was observed by refraining from any dishonest conduct, such as manipulating research methods and data or retaining data.

4. Findings and Discussion

This section considered the profile of the respondents and the presentation and discussion of the generated themes and categories of the strategies for incorporating sustainable construction material utilisation in Zimbabwe.

4.1. Profile of respondents

Interview invitations were sent to 20 respondents, and 16 were successfully conducted via phone calls and virtual meeting platforms. According to Hennink et al. (2017), 16-24 interviews are adequate to achieve meaning saturation for an in-depth understanding of issues. This study achieved saturation after the 15th interview. The profile of the respondents is shown in Table 1. Regarding educational qualifications, the analysis shows that 75% of the respondents had postgraduate qualifications, whilst 25% had an Honours degree. In terms of experience, 31.25% had more than 20 years, followed by 16-20 years and 6-10 years, and only 6.25% had 0-5 years. The interviewees were largely in high-level management positions. The percentage distribution was ideal because there were diverse perspectives from diverse professional backgrounds, as Burton (2021) echoed.

Table 1: Demographic profile of respondents

Interviewee	Level of education	Experience	Organisation	Position
1	Bachelor's degree	8	Green Building Council	Chief Executive Officer
2	Master's degree	20	Scientific Research Centre	Chief Executive Officer
3	Professor	38	Research Consultancy firm	Chief Executive Officer
4	Master's Urban Planning	11	Architectural firm	Chief Executive Officer
5	Bachelor's degree in engineering	11	Architectural firm	Projects Manager
6	Master's: Energy Engineering	4	Research Consultancy firm	Environmental Engineering/Sustainability Consultant
7	Bachelor's degree	10	Non-profit community-based organisation.	Co-founder, project development/training
8	Master's in Architecture	7	Architectural firm	Energy and Sustainability Auditor
9	Professor of Urban and Regional Planning	17	University	Pro Vice-Chancellor, Academic Affairs
10	Professor of Architecture	40	Architectural firm	Principal Architect
11	PhD Construction Management	21	University	Dean
12	Masters of Architecture	15	Architectural firm	Principal Architect
13	MSc Water Resources Engineering and Management	19	Civil Engineering Firm	Manager
14	Masters of Architecture	15	Entrepreneur	Director
15	Masters of Architecture	9	Architectural Firm	Director
16	Bachelor's degree	10	Ministry of Local Government and Public Works	Acting Deputy Director, Architectural Services

4.2. Modifications to Zimbabwe's Modern Building By-Laws (MBBL)

Interview participants were requested to suggest ways to incorporate sustainable construction material utilisation into the local Model Building By-Laws to promote their adoption. The extracted themes are presented in Table 2.

Table 2: Results- Themes, categories and codes

Theme	Category	Codes
Generation of modern by-laws with relevant and sustainable material promotion.	• Align with modern construction practices.	• Flexibility • New construction methods/practices
	• Stakeholder engagement	• Local materials • Incentives
Design-related modifications	• Material-specific	• Emphasise performance • Testing • Carbon calculation
	• Strategic	• Guidelines for consultation • Exploration/ research
Adopt green building principles or methodologies.	• Green building principles	• Green building codes • Energy efficiency • Embodied carbon • Climate change resilient
	• Green building instruction	• Training • Green skills

The extracted themes included the position that the Model Building By-Laws (MBBLs) of 1977 were unsuitable and insufficient to achieve sustainable construction goals and required more comprehensive consultation. The contributions from interviewees revealed three (3) themes: the generation of modern by-laws with relevant and sustainable material promotion, design-related modifications, and the adoption of green building principles and methodologies. The cradle-to-grave model is foundational in shaping the themes of modern by-laws, with relevant and sustainable material promotion and the adoption of green building principles and methodologies. The themes emphasise the promotion of human safety and protection of the environment as espoused by the theory. On the other hand, the theory of diffusion of innovation is situated in the themes of design-related modifications and adoption of green building principles and methodologies. The themes emphasise innovation in sustainable material promotion and green building methodologies; the communication of green building principles and methodologies; the rate of adoption of the suggested interventions; how the social construct influences adoption; and the adopter categories. The theme and categories are discussed hereafter.

4.2.1. Generation of a modern MBBL with relevant, sustainable material promotion

There is consensus that the MBBL document does not align with modern-day construction practices. MBBL should address challenges that may not have existed when they were formulated in 1977. MBBLs must align with modern construction practices and enable continuous participant engagement in this regard. In addition, the by-laws must address the current concerns highlighted by Interviewees 2, 7, and 13.

Interviewee 2: *…… by-laws should speak to climate resilient infrastructure……*

Interviewee 7: *room for developers to use alternative sustainable materials in the approved plans.*

Interviewee 13: *Model Building By-Laws must be revised and modernised to adapt to current trends, standards and practices in the construction sector.*

The views of Interviewees 2 and 13 align with Hoxha and Lecaj (2024), who argue that planning laws must adapt to current trajectories of sustainability development. The added advantage is that the views emanate from a researcher and a construction professional. MBBLs must be dynamic and align with modern construction practices. However, the interviewees did not clarify how best to achieve this. Despite these assertions, caution must be taken when aligning with modern construction practices within developing countries, as the level of industrialisation is a significant factor in any consideration. This is alluded to by Mathiyazhagan et al. (2019) regarding the gap between the challenges and the capabilities of developing countries, such as Zimbabwe. MBBL should allow flexibility, as supported by Interviewee 7. Stakeholders must be allowed to incorporate new and better sustainable materials, as and when they enter the market. However, due diligence must not be secondary; the approval process must be swift, sound, and supported by adequate research and development. Respondents suggested that minimal bureaucratic processes and procedures should be included within an addendum for approval and adoption of sustainable materials. Implementation and reference to addenda are critical (Chirisa, 2014), but they may not be incorporated as standard operating procedures due to potential administrative challenges. Hence, such addenda must be well supported by progressive policies (Kylili, 2017).

Continuous stakeholder engagement is pertinent if the by-laws are to remain relevant, as Interviewee 1, Interviewee 4, and Interviewee 8 argue. The green building and construction professionals reach a consensus on stakeholder engagement, as outlined hereafter.

Interviewee 1*: Include sustainable alternative local materials.*

Interviewee 4: *stakeholder engagements are important.*

Interviewee 8: *Firstly, they should be improved to reward sustainable practices to motivate developers and professionals.*

Stakeholder engagement promotes the adoption and acceptance of sustainable local materials, especially when incentives are provided to developers and professionals. Hoxha and Lecaj (2024) supported this notion by highlighting that, to ensure the enforcement of labelled materials in practice, by-laws should include tax levies and information for end users. The interviewees suggest a section within the MBBLs that stipulates rewards or incentives for sustainable practices to motivate developers and professionals. Despite the suggestion, it may be important to ensure that the construction material supply value chain is adequately resourced to meet the need for sustainable construction materials, as this is problematic in developing countries like Zimbabwe (Sakutemba et al., 2024). A recommendation for incentives within the by-laws was further suggested for designers and developers, as stated by Interviewee 12.

Interviewee 12: *In practice, the central issue around practice is compliance with regulations that are set. You need to go back to those regulations, not some annexure or deviation committee. Very few people know about these, and no one is willing to go through all that. Imagine spending three years trying to get your material approved. You will not have the money to build afterwards. Let us fix the regulations. It could be a carrot-and-stick approach: you do not have to force everyone, but you can say, "If you protect the environment, you get so many credits or tax rebates." Incentivise the adoption of sustainable materials. There is a need to deliberate at all levels throughout the building chain and to reduce energy demand by adopting sustainable construction materials.*

Still, such suggestions demand a multi-pronged approach that aligns all construction-related policies related to procurement, construction contract administration, environmental policy, and waste management. When this is achieved, stakeholders can be encouraged to incorporate sustainable construction materials in their day-to-day construction activities.

4.2.2. Design-related modifications

Within this theme, categories of material-specific and strategic modifications were extracted. The MBBL were deemed too prescriptive and needed to test and encourage new methods, thus allowing professionals to propose new materials for inclusion in standards and to enable embodied carbon calculation, as highlighted by Interviewees 10, 3 and 5.

Interviewee 10: *I find that the Model Building By-laws need to be more prescriptive on how to build. They should have standards that test and encourage new methods. I mean, architects should be allowed to propose new materials after proper testing for inclusion in standards and by-laws.*

Interviewee 3*: So, I think they need to drop the reference to cement altogether and just have things about performance. Can your material do this? Then you can do this with it.*

Interviewee 5: *Should include embodied carbon, which is measurable*

Design flexibility may be beneficial, as designers can add value by selecting alternative materials for their clients. This view is supported by Nasier (2021), who argued for practical material selections aligned with current sustainability practices. In addition, designers must be permitted to implement circular principles in their designs if the material's performance is guaranteed. This approach is reinforced by Singh and Kumar (2023) through their by-laws, which provide for reducing, reusing, and recycling to achieve zero landfills. For these suggestions to work, it is important that designers are given the freedom to develop better design codes that address existing concerns. This endeavour is more complex than it reads. It requires a concerted effort by tertiary institutions, industry, and research and development organisations to implement a well-regulated and flexible design regime, which can be onerous for a developing country like Zimbabwe. However, the idea can be initially implemented at a smaller scale and nurtured over time to realise the goals of sustainable construction material adoption.

The incorporation of design-related modifications must be strategic. Interviewees suggested that it be made mandatory for designers to incorporate sustainable building materials and promote buy-in from stakeholders. Conversely, flexibility is not supported by imposing "mandatory" inclinations on designers. However, this means guidelines must be developed and continually improved while consistent research and development are implemented. This is alluded to by Interviewees 6 and 13.

Interviewee 6: *Include guidelines for sustainable materials consultation in the MBBLs to encourage exploration, use as a reference, and include embodied carbon guidelines*

Interviewee 13: *Buy-in from all stakeholders. Increase funding for research in such construction technologies. Increase visibility and marketing of such products. Make sure such materials go through a standardisation process.*

However, the modifications can only be made after testing and approving sustainable materials and technologies. Fini and Akbarnezhad (2019) support such modifications if they are cognisant of the impacts of such sustainable material considerations. While this is true, the reality is that tested solutions, such as stabilised earth (Zami, 2014), have yet to be implemented, which further complicates regulatory frameworks and their modification for implementation. This will make it more difficult for construction industry researchers and professionals to recommend and construct using sustainable materials. Some interviewees emphasised that by-laws should address climate-resilient infrastructure and alternative materials, encouraging their exploration as addenda. This view came from researchers, who are more knowledgeable about the current challenges in the construction sector.

Notwithstanding this, the apparent gap between research and on-the-ground implementation must be reduced to enhance the development of practical solutions. Further suggestions included creating a sustainable construction policy to serve as a reference for the MBBL. Again, the reality is that design-related modifications require that all designers be conversant with sustainable construction before they can design sustainably.

4.2.3. The adoption of green building methodologies in MBBLs

This theme comprised the categories of green building principles and green building instruction. Some respondents recommended attention to green building principles, including interviewees 4 and 16.

Interviewee 4: *Speaking to energy efficiency in the MBBLs, working on affordable housing building guidelines, and providing them with carbon calculations.*

Interviewee 16: *A green building code may also be formulated, adopted and enforced as an addendum to the Model Building By-laws."*

This is significant, coming from a construction professional and a government official. It shows that the government recognises the importance of promoting green building principles. As suggested by Fini and Akbarnezhad (2019), considering the environmental impact of the material, such as carbon footprint analysis and energy efficiency, is pertinent. As such, energy efficiency is to be included in the MBBLs with accompanying embodied carbon calculations as a critical material performance criterion. However, the practicability of this is remote. Zimbabwe is not yet ready to implement green building and construction as alluded to by Mafuku (2019). If this is still the case, this suggestion would be difficult to implement. In addition, the failure to align procurement with the need to adopt sustainable construction materials is detrimental. In addition, other respondents felt that a chapter on sustainable design, with credits for using sustainable construction materials, was necessary, as reported by Interviewee 16. India's Model Building By-laws of 2016 include green building and sustainability provisions, including sections on applicability, sanction requirements, and various green rating system guidelines (Singh and Kumar, 2023). These by-laws are supported by adequate infrastructure to achieve them, which may not be relevant for Zimbabwe. In addition, Hoxha and Lecaj (2024) revealed that including sustainability in the by-laws without specifying conformity guidelines for sustainable materials would not motivate their adoption in construction practice, but would instead remain at an experimental level. Zami (2014) already confirmed this within the Zimbabwean context. Along with this, there were supposed to be affordable housing and public building guidelines that address the use of sustainable materials, so that the government leads from the front. Unfortunately, the comments from government officials expose their lack of readiness to implement this, despite the practice being supported by Hoxha and Lecaj (2024), who argue that the inclusion of green labelling in drafting by-laws makes it easier for consumers to identify sustainable products and technologies.

In green building instruction, the importance of training construction professionals in green building principles and technologies, and the need for research and standardisation of green building materials, are paramount. Interviewees 9 and 15 highlight the significance of training and skill sets. It is paramount that these comments are coming from an academic and a construction professional.

Interviewee 9: *Use existing policies and demo structures for training.*

Interviewee 15:*….needs skillset to calculate parameters…..*

Adequate technical support systems are essential if green building principles are to be adopted. Kylili (2017) and Mogaji et al (2024b) allude to the importance of supporting the implementation of green building technologies through enhancing awareness and encouraging competent standardisation processes for practical solutions. Inversely, Kativu et al. (2023) attribute the lack of adequate trainers and training to inadequate instruction on construction material waste management. This means the country needs to leverage external partners to achieve adequate green building instruction. The importance of training building inspectorates in the application of sustainable construction materials through tertiary institutions and vocational colleges is also pertinent.

Cumulatively, emphasis was placed on the need for governments to lead implementation to build stakeholder confidence. Government projects needed to adhere to any alterations to the MBBL to ensure that state construction projects used sustainable construction materials. Along with this, there were supposed to be affordable housing and public building guidelines that addressed the use of sustainable materials, so that the government led from the front. This practice is supported by Hoxha and Lecaj (2024), who argue that the inclusion of green labelling in drafting by-laws makes it easier for consumers to identify sustainable products and technologies. Smith (2015) revealed that other developing countries, such as India, had adopted the green rating systems to promote the inclusion of sustainable materials. A green building code needs to be formulated, adopted, and enforced, and it should also be included as an addendum to the Model Building By-laws. Relative acts needed to be updated to include allowances for the use of natural resources, with provision for replenishment procedures within specific time intervals. For example, any regulations must be advanced by government departments as supported by Mogaji et al (2024a).

5. Conclusion and Further Research

The literature review and interviews indicated that the by-laws were limiting, to a large extent, the adoption of sustainable construction materials. As such, recommendations for generating modern MBBL with relevant, sustainable material promotion must be included in the key strategies. The other recommended modifications are design-related and involve adopting green building principles or methodologies in MBBLs. There was insistence that all modifications be made through extensive stakeholder consultation and participation to ensure buy-in to the regulations, which, in turn, would make implementation easier. A comparison with the literature review supported these suggestions. However, the challenges peculiar to Zimbabwe limit the uptake of some of these recommendations, hindering Zimbabwe's progress in aligning with current global discussions, challenges, and trends. For example, design flexibility may contribute to a chaotic administrative process within local authorities.

The study contributed pertinent strategies that can be incorporated into the modification of the existing Model Building by-laws to drive the sustainable construction agenda. The study contributed key interventions aligned with the need to promote human and environmental safety (cradle-to-grave model) and promote innovation in the adoption of sustainable construction materials (diffusion of innovation). In particular, the study recommends that the Government of Zimbabwe should create a new and updated Model Building By-laws based on the use of sustainable or circular materials and developed through a thorough stakeholder participation programme that includes researchers, academics, construction professionals, and material suppliers, among others. The adoption of any innovations regarding sustainable construction materials must be founded on inclusive, well-established communication channels (through the various construction-related policies, including the MBBLs), be timeously responded to, and have a positive impact on existing social systems (cultural systems that influence the design and use of construction materials). The generation of practical interventions is supported, while the modification of construction-related policies is identified as fundamental to achieving the integration of sustainable construction materials. A comprehensive stakeholder-initiated review of the existing Model building by-laws that align with holistic sustainability goals is recommended. Further studies can examine piloting the implementation of a revised by-law chapter in a selected municipality or conducting a quantitative assessment of developers' willingness to adopt labelled materials under various incentive schemes. The main limitation was the exclusive use of a key-informant qualitative design rather than end users. However, the exploratory nature of the study supported the approach.

References

Agyekum, K., Adinyira, E. & Oppon, J. A., (2022). Factors limiting the adoption of hemp as an alternative sustainable material for green building delivery in Ghana. International Journal of Building Pathology and Adaptation, 40(2), pp. 202-218. DOI 10.1108/IJBPA-11-2020-0100

Altuma, M. I., & Ghasemlounia, R. (2021). Effects of Construction Materials to Achieve Sustainable Buildings. 11 (1), https://doi.org/10.31033/ijemr.11.1.4

Babbie, E. & Mouton, J. (2015). *The practice of social research.* South African Edition. Contributions by Vorster, P. & Prozesky, B. Southern Africa. Capetown: Oxford University Press.

Baloi, D. (2003). Sustainable construction: challenges and opportunities. In: Greenwood, D J (Ed.), 19th Annual ARCOM Conference, 3-5 September 2003, University of Brighton. Association of Researchers in Construction Management, Vol. 1, 289-97.

Bolognesi, M., Pilgram, R. & Van Den Heerik. R. (2016). Reliability in content analysis: the case of semantic feature norms classification. *Behaviour Research Methods,* 49: 1984-2001. doi:10.3758/s13428-016-0838-6.

Braun, V., & Clarke, V. (2022). Conceptual and design thinking for thematic analysis. Qualitative psychology, 9(1), 3.

Braungart, M., & McDonough, W. (2009). Cradle to cradle. Random House.

Brennan, M. C. E. (2015). Sustainable Construction in the 21st Century: An Educational Perspective on Shifting the Paradigm. Liverpool John Moores University (United Kingdom). Available at: /https://researchonline.ljmu.ac.uk/id/eprint/4532/2/157999_FINAL%20THESIS%20PDF.pdf, Accessed on 15 September 2025

Burton D.E. 2021. Demographic Research: The Big Picture in Research. Available at:https://www.researchgate.net/publication/348845012_Demographic_Research_article. Accessed on 22 April 2025.

Chari F. and L. Chiriseri. (2014). Barriers to Sustainable Procurement in Zimbabwe. Greener Journal of Business and Management Studies. Vol. 4 (1), pp. 014-018. ISSN: 2276-7827

Chirisa, I. (2014). Building and urban planning in Zimbabwe with special reference to Harare: Putting needs, costs and sustainability in focus. Consilience, (11), 1-26.

Crowther, S., and Thomson, G. (2020). From Description to Interpretive Leap: Using Philosophical Notions to Unpack and Surface Meaning in Hermeneutic Phenomenology Research. International Journal of Qualitative Methods. 19: 1-11, https://doi.org/10.1177/1609406920969264

Demir, İ., & Doğan, C. (2020). Physical and mechanical properties of hempcrete. Open Waste Manag. J, 13(1), 26-34. DOI: 10.2174/1874312902014010026

Eze, E. C., Sofolahan, O., & Omoboye, O. G. (2023). Assessment of barriers to the adoption of sustainable building materials (SBM) in the construction industry of a developing country. Frontiers in Engineering and Built Environment, 3(3), 153-166. DOI 10.1108/FEBE-07-2022-0029

Eze, E. C., Ugulu, R. A., Onyeagam, O. P., & Adegboyega, A. A. (2021). Determinants of sustainable building materials (SBM) selection on construction projects. International Journal of Construction Supply Chain Management, 11(2), 166-194. DOI:10.14424/ijcscm110221-166-194

Fini, A. A. F., & Akbarnezhad, A. (2019). Sustainable Procurement and Transport of Construction Materials. In Sustainable Construction Technologies (pp. 161-209). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-811749-1.00005-5

Global Climate Risk Index (2021). Who suffers Most from Extreme Weather Events? Weather-related Loss Events in 2019 and 2000 to 2019. Available at: https://www.germanwatch.org/en/19777 Acces sed on 22 June 2023

Government of Zimbabwe. 1977. Model Building By-Laws. Government of Zimbabwe: Harare. Available at: https://www.zezuru.digital/Library/model-building-by-laws/ Accessed on 14 September 2025

Hennink, M. M., Kaiser, B. N., & Marconi, V. C. (2017). Code saturation versus meaning saturation: how many interviews are enough?. Qualitative health research, 27(4), 591-608. DOI: 10.1177/1049732316665344

Hoxha, V., & Lecaj, V. (2024). Regulatory barriers to implementing sustainable buildings in Kosovo. Property Management, 42(2), 293-309. https://doi.org/10.1108/PM-01-2022-0008

Kativu, R. R., Chigara, B., & Smallwood, J. (2023). Barriers to managing construction material waste in Zimbabwe. Association of Schools of Construction of Southern Africa. ASOCSA 17th Built Environment Conference; 09 - 10 October 2023, CSIR International Convention Centre, Pretoria, South Africa

Kibert, C.J (2022). Sustainable Construction Green Building Design and Delivery Fifth Edition, John Wiley & Sons, Inc., Hoboken, New Jersey, Book ISBN 9781119706465

Kylili, A., & Fokaides, P. A. (2017). Policy trends for the sustainability assessment of construction materials: A review. Sustainable Cities and Society, 35, 280-288. https://doi.org/10.1016/j.scs.2017.08.013

Lee, J. J., Ramjan, L., Nuampa, S., & Lai, C. K. Y. (2023). Where is the interpretation? Important considerations for the philosophical and disciplinary lenses in qualitative health research. Nursing and Health Sciences, 25(4), 493. https://doi.org/10.1111/nhs.13068

Leedy, P.D. & Ormrod, J.E. (2013). Practical research: planning and design. 10th ed. New Jersey: Pearson Education.

Mafuku, S. H. (2019). Greening the construction industry in Zimbabwe. Book Chapter in The Sustainability Ethic in the Management of the Physical, Infrastructural and Natural Resources of Zimbabwe, p 361. Publisher: Langaa RPCIG, Cameroon, ISBN: 9789956550456

Mathiyazhagan, K., Gnanavelbabu, A. & Lokesh Prabhuraj, B. (2019). A sustainable assessment model for material selection in construction industries perspective using hybrid MCDM approaches. Journal of Advances in Management Research, 16(2), 234-259. https://doi.org/10.1108/JAMR-09-2018-0085

Mogaji, I. J., Mewomo, M. C., & Bondinuba, F. K. (2024a). Assessment of barriers to the adoption of innovative building materials (IBM) for sustainable construction in the Nigerian construction industry. Engineering, Construction and Architectural Management, 32(13), 1-26. https://doi.org/10.1108/ECAM-04-2024-0430

Mogaji, I., Mewomo, M., Bondinuba, F. K., Aboagye-Nimo, E., & Abraham, Y. (2024b). Drivers Influencing the Adoption of Innovative Building Materials (IBM) for Sustainable Construction in Nigeria. Human Factors in Design, Engineering, and Computing, 159(159). https://doi.org/10.54941/ahfe1005741

Moyo, T., Mudombo, M.V., Mazen, M.M. and Moyo, C. (2024). Barriers to the adoption of sustainable construction materials in Zimbabwe. International Journal of Building Pathology and Adaptation, Vol. ahead-of-print No. ahead-of-print. https://0-doi.org.wam.seals.ac.za/10.1108/IJBPA-04-2024-0076

Nasier, S. (2021). Sustainable green materials for new construction. Materials Today: Proceedings, 37, 3505-3508. https://doi.org/10.1016/j.matpr.2020.09.396

Onyegiri, I., & Ugochukwu, I. B. (2016). Traditional building materials as a sustainable resource and material for low cost housing in Nigeria: Advantages, challenges and the way forward. International Journal of Research in Chemical, Metallurgical and Civil Engineering, 3(2), 247-252. ISSN 2349-1442 EISSN 2349-1450

Resnik D.B. (2020). What Is Ethics in Research & Why Is It Important? Available at: https://www.niehs.nih.gov/research/resources/bioethics/whatis/index.cfm. Accessed on 30 September 2025.

Sakutemba, N., Muvungani, R. & Moyo, T. (2024). Barriers to the adoption of Electronic Procurement in public sector construction projects in Zimbabwe. Journal of Construction in Developing Countries, 29(2), 231–255. DOI:10.21315/jcdc-12-23-0170

Saunders, M., Lewis, P. and Thornhill, A. (2016), Research Methods for Business Students, 7th ed. Pearson Education, London.

Singh, R., & Kumar, A. (2023). Sustainable materials and green building practices in India: A policy and performance review. Journal of Green Construction and Design, 12(2), 45–59.

Smith, R. M. (2015). “Green” building in India: a comparative and spatial analysis of the LEED-India and GRIHA rating systems. Asian Geographer, 32(2),73-84. https://doi.org/10.1080/10225706.2015.1020065

Tran, Q., Nazir, S., Nguyen, T. H., Ho, N. K., Dinh, T. H., Nguyen, V. P., & Kieu, T. S. (2020). Empirical examination of factors influencing the adoption of green building technologies: The perspective of construction developers in developing economies. Sustainability, 12(19), 8067. https://doi.org/10.3390/su12198067

United Nations. (2020). The Sustainable Development Agenda. Available at: https://www.un.org/sustainabledevelopment/development-genda/#1b1981a30bdd8fde2. Accessed on 19 June 2025

United Nations Climate Technology Centre and Network (CTCN) (2022). Available at: https://www.ctc-n.org/technical-assistance/projects/development-green-building-standards-zimbabwe. Accessed on 22 June 2025.

Vaismoradi, M., Turunen, H., & Bondas, T. (2013). Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. Nursing & health sciences, 15(3), 398-405. doi: 10.1111/nhs.12048

Wani, T. A., & Ali, S. W. (2015). Innovation diffusion theory. Journal of general management research, 3(2), 101-118. ISSN 2348-2869

Zami, M. S. (2014). Drivers and their Relationship with Inhibitors Influencing the Adoption of Stabilized Earth Construction to Alleviate Urban Housing Crisis in Zimbabwe. Key Engineering Materials, 632, 119–144. https://doi.org/10.4028/www.scientific.net/kem.632.119.

JCBM (2025) 8(S1) 111-124

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Constraining Sustainability: A Critical Examination of Construction Policy and Practice in Nigeria

Nishani Harinarain[1] and Ayotunde Babalola[2]

[1&2]School of Engineering, University of KwaZulu-Natal, South Africa

Received 11 October 2025; received in revised form 14 October 2025, 19 December 2025; accepted 28 December 2025
https://doi.org/10.15641/jcbm.8.S1.1938

Abstract

This paper examines the policy-related challenges faced by stakeholders in promoting sustainable construction practices within Nigeria's construction sector. The research objective was pursued through a comprehensive literature review and semi-structured interviews with eleven built environment professionals based in Lagos and Abuja. Using NVivo 14, a thematic analysis was conducted, yielding seven key themes. Among these, the most significant were the weak enforcement of the Nigerian building code, limited public and professional awareness of sustainable construction, and insufficient municipal capacity to support implementation at the local government level. The findings underscore the need for stronger regulatory frameworks, clearer enforcement mechanisms, and a coordinated awareness strategy to support policy adoption and compliance. The study also highlights the need for active political will, alongside stakeholder collaboration, to ensure policy continuity and mitigate the effects of changing government administrations. Government agencies, policymakers, and industry professionals must therefore collaborate more strategically to drive innovation and strengthen policy adaptation mechanisms. Overall, this study advances knowledge of sustainable construction policy in developing economies by presenting practitioner-based evidence on Nigeria's specific challenges in policy implementation and political will, from the perspective of senior construction industry professionals.

Keywords: Building code, Nigeria, policy implementation, professionals, stakeholders, and sustainable construction

1. Introduction

Sustainable construction has become a core global priority as nations seek to balance economic development with environmental protection and social well-being. Policy frameworks play a critical role in guiding this transition by shaping regulatory expectations, setting performance standards, and defining accountability mechanisms within the construction sector (Babalola & Harinarain, 2024; Hudson, Hunter, & Peckham, 2019). In contexts where government regulation is weak or inconsistently enforced, sustainability outcomes are often compromised (Isang, 2023).

Nigeria's construction industry illustrates this challenge. Despite increasing discourse on sustainability, the sector continues to face persistent structural and policy-related challenges, including recurring building collapses, limited uptake of sustainable technologies, and poor compliance with environmental standards (Babalola & Harinarain, 2024). Stakeholders cite weaknesses in policy formulation, enforcement capacity, political will, and municipal-level implementation as core barriers to sectoral transformation (Akadiri, Chinyio, & Olomolaiye, 2012).

This study is guided by a policy implementation gap and institutional governance lens, recognising that policies often fail not at the design stage but during execution, due to weak institutions, fragmented accountability, and low political commitment (Isang, 2023). These ideas shaped the development of the interview guide, which focused on regulatory enforcement, municipal responsibility, rating systems,

[1] Corresponding Author
Email address: harinarain@ukzn.ac.za

and capacity constraints.

Accordingly, this study aims to examine the policy challenges stakeholders face in implementing sustainable construction practices in Nigeria, acknowledging that policy instruments can institutionalise sustainability as an industry standard rather than an individual preference. Two research questions guide this study:
RQ1: What institutional and policy implementation barriers hinder the effective adoption of sustainable construction practices in Nigeria?
RQ2: How do practitioners perceive the current level of regulatory enforcement, political will, and municipal capacity within the Nigerian construction sector?

Compared to other developed nations, several countries, including the United Kingdom, Australia, South Korea, China, and Japan, have made substantial progress in integrating sustainability into their construction sectors. Through comprehensive policy frameworks and both regulatory and non-regulatory measures, these countries have successfully addressed key sustainability concerns, such as material consumption, waste reduction, and resource management, while ensuring social equity and environmental protection (Solanke & Fapohunda, 2016). In the UK, for example, strong central government leadership, mandatory performance standards, and cross-sector coordination have supported efforts to enhance material efficiency, improve waste management, and reduce carbon emissions (Heijden & Bueren, 2013). These international achievements served as sensitising concepts for this research, guiding expectations around what effective sustainability governance might require in Nigeria—such as strengthened enforcement, locally relevant rating systems, and improved municipal oversight.

However, Nigeria remains constrained by fragmented institutional arrangements, weak monitoring systems, and limited collaboration among public agencies, practitioners, and local governments. Understanding these policy challenges is critical for developing strategies that align the country's construction sector with global sustainability ambitions and ensure that public policies translate into measurable outcomes rather than aspirational statements.

2. Sustainable Construction in Nigeria

Nigeria, a federal nation of 36 states and 774 local government areas, faces significant coordination and institutional challenges in implementing national development policies (Federal Republic of Nigeria, 2006). These administrative complexities affect the construction sector, where fragmented authority contributes to inconsistent interpretation and enforcement of regulations.

The Nigerian construction industry policy development initiatives are still at a very early stage and are evolving more slowly than in other developed nations such as the United Kingdom and Australia (Oyewobi & Jimoh, 2022; Onuoha et al., 2017). While research on green building is expanding, scholars observe that policy formulation and institutional capacity-building have not progressed at the same pace (Onuoha et al., 2017). Sustainable building practices, skills development, and environmental performance frameworks remain weak, primarily due to inadequate legislation, low political prioritisation of sustainability, and fragmented institutional structures (Oribuyaku, 2015).

Sustainable construction implementation challenges in Nigeria align with findings from governance and policy implementation theory, particularly the "implementation gap" model, which argues that policy failure often stems from weak administrative capacity, lack of clarity, fragmented authority, and insufficient resources (Hill & Hupe, 2014). These conceptual ideas underpin the literature reporting that Nigeria's sustainable construction efforts have been constrained not simply by absent policies but by weak enforcement, low state capacity, and inconsistent political will (Isang, 2023; Oyewobi & Jimoh, 2022).

2.1. Policy barriers to sustainable construction in Nigeria

Multiple studies emphasise that the absence of a coherent sustainability framework is a significant barrier to policy implementation within Nigeria's construction sector (Davies & Davies, 2017; Isang, 2023). Government policies should generally favour sustainable construction and energy savings, given their impacts on the quality of life of the citizenry (Isang, 2023). Usually, when implemented, these policies should help the built environment become safer to work in, more efficient through the presence of frameworks and a desired strategy, and sustainable in terms of efficient service delivery to its clients (Akadiri et al., 2012).

Currently, there are no established policies, regulations, professional councils, or bodies to enhance knowledge in the sustainable construction domain and promote socio-economic and environmental sustainability (Isang, 2023). Although initiatives such as the 2011 Global Environment Facility programme and the Building Energy Efficiency Code (BEEC) introduced in 2018 demonstrate government awareness (Atanda & Olukoya, 2019; Geissler et al., 2018), these reforms have not translated into widespread sectoral change. The literature links this gap to limited government capacity, weak monitoring structures, and inadequate political commitment to sustainability agendas.

Regarding existing environmental protection laws and the need for new laws, Nwokoro and Onukwube (2015) noted that the advancement and strengthening of municipal by-laws for major urban communities in Nigeria should be supported and encouraged, given their significant improvements. While Governments are responsible for nurturing the economy, they must drive corporate sustainability through legislation and benefits/penalties (Isang, 2023).

Teething problems associated with implementing new initiatives in an existing industry, such as the need to improve technical know-how and skills on sustainable construction, low awareness and insistence on sustainable construction techniques on sites and during construction processes by clients and enlightened professionals and lack of adequate expertise are perceived as barriers to adequate implementation of sustainable construction from the industry stakeholders' perspective (Bungwon, et al., 2016), these can be controlled with adequate policies being implemented as argued by (Goh et al., 2020). Most of these barriers are believed to be adequately overcome by adequate policies.

Policies, regulations, and professional guidelines on sustainable construction and development should be taken very seriously by the government, as the consequences of inaction in this regard are dire (Davies & Davies, 2017). In Nigeria, the lack of sustainability in construction projects is evident, with apparent deviations from ideal sustainability principles. Infusing these principles is crucial to enhancing the construction environment in Nigeria, thereby preventing further building collapses and promoting capital and economic growth (Isang, 2023).

2.2. Status of the Nigerian Building Code

Building codes establish the fundamental regulations for construction quality, with area-specific bylaws strengthening requirements in urban centres. Such codes form the foundation for all construction policies in developed nations, such as the United Kingdom (Gibbs & O'Neill, 2015) and Denmark (Drysdale, Mathiesen, & Paardekooper, 2019). However, the building code in Nigeria lacks regulatory backing and is rarely implemented in practice (Geissler et al., 2018).

There is an urgent need to revise and strengthen the Nigerian Building Code to support sustainable construction. Critics argue that the code lacks enforcement power and has low implementation rates (Ogunbiyi, 2014). While the code sets minimum construction standards, its application begins at the local government level through the Building Code Advisory Committee (BCAC) (Federal Republic of Nigeria, 2006). Some scholars propose that sustainable construction should be driven at the municipal level (Babalola & Harinarain, 2024); however, the Nigerian building code has not been adequately empowered to establish minimum infrastructure requirements for sustainable construction. Moreover, inconsistent professional adoption has led to uneven implementation across the industry (Isang, 2023).

Nigeria was registered as a prospective member of the World Green Building Council in 2014 (WGBC, 2020). There is no active Green Building Council to further these interests and advise construction clients appropriately on sustainable construction (Babalola & Harinarain, 2024). The lack of an active green building council has adversely affected the growth of sustainable construction practices in the Nigerian construction environment. Nigeria currently lacks a construction strategy/ agenda. Firms and professional institutions only work according to client requirements and organisational preferences.

2.3. Green Building Council in Nigeria

Nigeria has been registered as a prospective member of the World Green Building Council (WGBC) since 2014 (WGBC, 2020). However, this affiliation has had minimal impact on advancing sustainable construction practices in the country (Akinyemi, Adekunle, Joseph, Anthony, & Dabara, 2019). Despite its membership status, Nigeria lacks an active Green Building Council capable of promoting sustainability initiatives or providing informed guidance to construction clients on environmentally responsible building practices. The absence of such an institutional body has significantly constrained the growth and mainstream adoption of sustainable construction principles within the Nigerian built environment. More broadly, the absence of an integrated national construction strategy or sustainability roadmap has been documented by Nigerian planning research, which notes that sector outcomes are left to project-level decisions rather than coordinated state priorities (Babalola & Harinarain, 2024). This aligns with institutional theory, which suggests that without a strategic centre, industries default to path dependency, informal practices, and short-term client-driven decision making (Scott, 2014).

3. Research Methodology

This study adopted an interpretive qualitative approach to explore the policy challenges associated with implementing sustainable construction practices in Nigeria. The interpretive paradigm was appropriate for this research because it seeks to understand how individuals construct meaning from their professional experiences and social contexts. Data were collected through semi-structured interviews with professionals in the Nigerian construction industry, allowing for in-depth exploration of personal insights, institutional dynamics, and contextual realities that shape policy formulation and implementation.

The target population consisted of construction industry professionals, including architects, quantity surveyors, builders, civil engineers, and urban planners. These categories were purposefully selected to ensure a broad representation of the built environment professions, as each discipline contributes distinct perspectives to the discourse on sustainable construction. Diversity of professional backgrounds was crucial for capturing a holistic understanding of the industry's challenges and opportunities in embedding sustainability principles.

3.1. Sampling and Participants

A purposive sampling strategy was employed to identify individuals with substantial experience and influence within the construction sector. The inclusion criteria focused on years of professional practice, familiarity with sustainability-related projects, and participation in policy or regulatory processes. These criteria ensured that participants could provide rich, informed reflections on both policy development and its practical implications.

Fifteen potential participants were compiled from professional associations and networks in Abuja and Lagos, Nigeria's administrative and commercial capitals. These two cities were chosen for their high concentration of construction activity, the presence of major policy institutions, and the diversity of professional expertise. Invitations were distributed via email and followed up with by phone calls. Eleven participants agreed to participate, which falls within the suitable range proposed for interpretive qualitative studies of this nature (Creswell & Poth, 2018; Tracy, 2012). Saturation was reached when no new substantive codes or insights emerged after the ninth and tenth interviews, supporting the adequacy of the final sample size.

Data saturation was used to validate the adequacy of the final sample size. Saturation was assessed continuously throughout coding and transcript comparison. Following the ninth and tenth interviews, no new substantive codes, perspectives, or conceptual categories emerged, indicating that core patterns were sufficiently captured across participant groups. This aligns with Hennink and Kaiser's (2022) argument that saturation in homogenous qualitative samples is often reached within the first 6–12 interviews. Consequently, the eleventh interview confirmed rather than extended the identified thematic boundaries, supporting the credibility and completeness of the final dataset.

While the qualitative sample does not support statistical generalisation, the depth, relevance, and professional seniority of participants offer strong analytical insights into Nigeria's policy implementation environment for sustainable construction.

3.2. Ethical Considerations

Ethical approval for the study was obtained from the institutional research ethics committee (Clearance Number: HSSREC/00000537/2019). All participants received written and verbal information explaining the project aims, the interview format, voluntary participation, and their right to withdraw at any time without consequences. Informed consent was obtained prior to participation. Confidentiality and anonymity were strictly maintained. Given the sensitivity of discussions involving political decision-making, enforcement failures and institutional corruption, particular care was taken to ensure that quotations could not be traced to identifiable individuals or organisations.

3.3. Data Collection

The semi-structured interviews were conducted face-to-face in participants' offices or open professional environments during working hours, as indicated in Table 1 (See Appendix 1). Each session lasted approximately 45 minutes. An interview guide was used to maintain consistency across discussions while allowing flexibility for participants to elaborate on emerging issues. All interviews were audio-recorded with participants' consent and subsequently transcribed verbatim for analysis. Field notes were also taken to capture nonverbal cues and contextual details that informed the interpretation.

3.4. Data Analysis and Coding

The data analysis followed a systematic, iterative approach consistent with the principles of thematic analysis. NVivo 14 software was used to assist in managing and organising the data. Analysis began with the preparation phase, where all recorded interviews were transcribed and verified against the audio files to ensure accuracy.

In the coding phase, the transcripts were read multiple times to familiarise the researcher with the content. Codes were assigned to meaningful units of text that captured key ideas, issues, or patterns related to the research questions. These initial codes were primarily descriptive, focusing on policy-related challenges, institutional roles, and implementation barriers.

During categorisation, related codes were grouped to identify emerging patterns and relationships within the data. Broader categories began to emerge around recurring issues, including weak regulatory frameworks, a lack of awareness, fragmented institutional coordination, and limited professional engagement in policy formulation.

The structuring stage involved refining these categories into coherent themes and sub-themes that encapsulated the core dimensions of the participants' experiences. Representative quotes were selected to support each theme, ensuring that participants' voices were authentically reflected in the findings.

Finally, the interpretation stage entailed synthesising the themes in light of existing literature and the study's conceptual framework. The researcher drew on professional experience and theoretical understanding to make sense of how the identified themes reveal systemic barriers to the implementation of sustainable construction policy in Nigeria.

4. Findings and Discussion

The results were transcribed and coded according to likely themes. Seven themes emerged, namely: the perception of professionals on sustainable construction practice in their location and the country generally, the significant challenges observed to the complete uptake of sustainable construction in the Nigerian construction industry, the interviewee's perception of the usage of the Nigerian building code, their ideas on improving sustainable construction practice through a policy, the need for strict policies and implementation mechanisms, stakeholder's inputs to improve sustainable construction practice and the possibility and capacity of the local government in the implementation and enforcement of sustainable construction policy. These are discussed below.

4.1. Perception of sustainable construction practice

Across the interviews, respondents consistently highlighted that sustainable construction in Nigeria remains at a rudimentary stage, with visible activities concentrated primarily in Lagos and Abuja. Outside these major urban centres, sustainable construction practices were described as virtually non-existent. As one participant explained, *"Being a new concept, the level of practice is very low; in Lagos, for example, you can count the number of houses built with sustainable materials"* (Participant 10). This statement highlights a growing awareness that, while sustainability principles are gaining recognition, their practical application remains limited to a small segment of projects and professionals.

Participants attributed this slow uptake largely to the absence of strong policy frameworks and weak regulatory enforcement. As noted by one respondent, *"More needs to be done about sustainable construction on the level of policies and adequate implementation"* (Participant 2).

The lack of coherent policy direction has, in effect, left the promotion and adoption of sustainable practices to individual or corporate discretion rather than institutional mandate. This aligns with earlier studies such as Ogunbiyi (2014) and Onuoha et al. (2017), who similarly observed that the sustainable construction agenda in Nigeria suffers from inadequate government commitment and fragmented policy implementation.

Several participants also identified the lack of political will as a critical barrier. Participant 8 observed that *"The level of sustainable construction practice is very low even in Lagos, which hosts most construction activities in the country."*

This reflects a broader concern that, despite Nigeria's growing construction market, environmental sustainability remains peripheral in national development strategies.

The interviews further revealed a mixed understanding of sustainable construction among professionals. Some acknowledged that the concept is gradually gaining traction within industry discourse.

Participant 1 remarked that *"Sustainable construction practice is at an evolutionary stage. The knowledge base necessary for implementation is increasing."*

Similarly, others recognised isolated advancements in Abuja, noting that *"It is averagely practiced in this location as this is a capital city (Abuja) but low in other parts of the country"* (Participant 4).

However, these comments were often accompanied by concerns about limited awareness and capacity-building efforts. As Participant 5 succinctly put it, *"Practice level is very low; awareness is also low."*

Collectively, these responses portray sustainable construction in Nigeria as being in its formative phase, characterised by low awareness, weak institutional support, and sporadic practice.

The findings suggest that while the discourse around sustainability is emerging, it lacks the systemic reinforcement necessary for large-scale adoption. This interpretation aligns with existing literature (Ogunbiyi, 2014), which emphasises that without robust policy support and coordinated stakeholder engagement, sustainable construction will continue to evolve slowly and unevenly across the country.

4.2. Major challenges to the complete uptake of sustainable construction

Respondents were then asked to identify the perceived significant challenges in implementing sustainable construction in the Nigerian construction industry, particularly in their local area. Results were categorised into four sub-themes: inadequate awareness and training; policy and educational issues; the absence of a building code; and the lack of political will to implement sustainable construction, as shown in Figure 1 and discussed below.

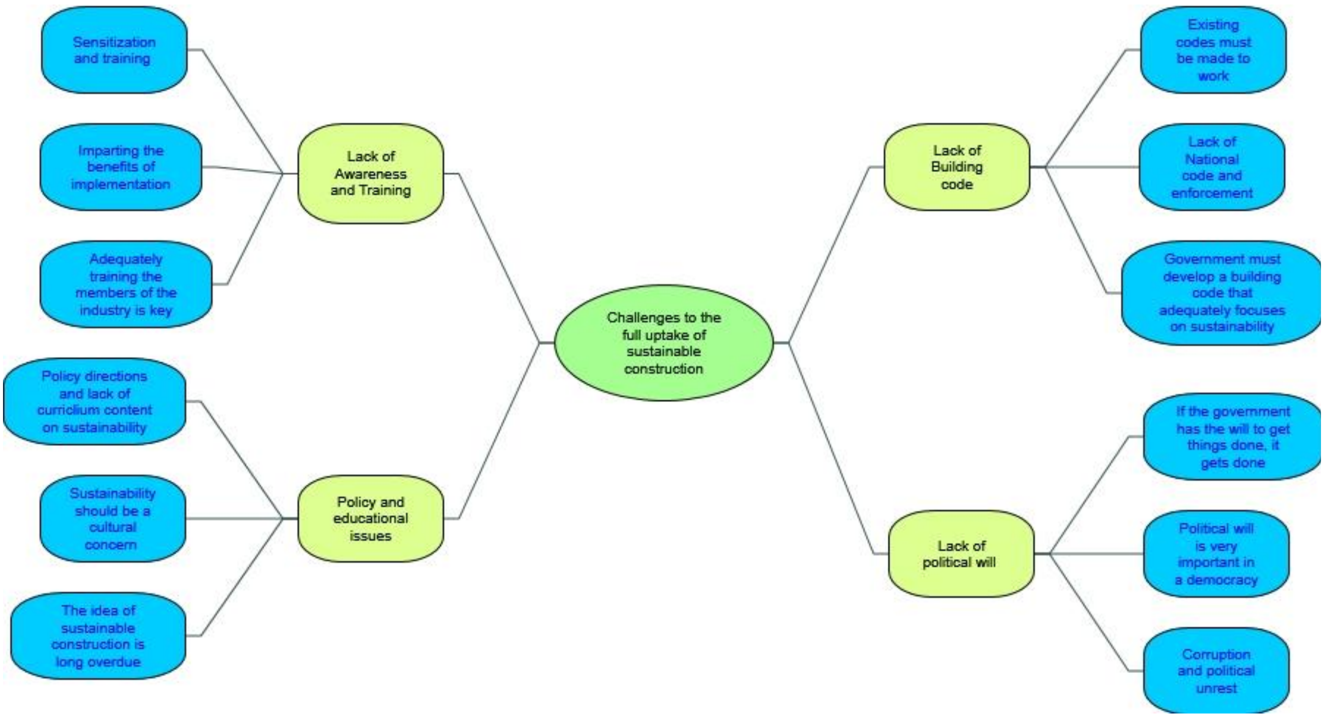

Figure 1: Sub-themes on challenges to the complete uptake of sustainable construction

Bungwon et al. (2016) identified a **lack of awareness and adequate training** as part of cultural enshrinements that are expected to improve industry knowledge of sustainable construction. The lack of adequate awareness was also confirmed in this study. Sensitisation and training were advocated to introduce people within and outside the industry to the basic knowledge and benefits of sustainable construction practices.

Davies and Davies (2017) highlighted the lack of policy enforcement and educational issues as key challenges in the literature. Participant 7 indicated that the absence of a government-laid-down plan or strategy for stakeholders to follow is challenging. The Nigerian construction industry lacks strategic short- and long-term goals for sustainable construction. Hence, there is a gap as knowledge of sustainable construction is not even taught to incoming professionals. The incoming professionals need to start learning experientially as it relates to the organisational ethos of the individual companies they work with; this is not ideal. The lack of current policy enforcement was a common comment from participants 2, 5, and 11, and it is a key barrier. It was noted that although the industry currently lacks an enforcement mechanism, no practising professional wants to be seen as on the wrong side of the law. Therefore, if the policy is actively implemented with necessary enforcement mechanisms, the likelihood of success is high.

The lack of adequate and sustainable building codes emerged as a challenge. There are problems with enforcing the existing building code, as stated by Participant 1, and formulating a new sustainable building code is not exactly forthcoming unless underlying issues with the non-performing building code are resolved (Participant 10). These underlying issues include the lack of teamwork and harmony among professional institutions in the country, the lack of a coordinating agency/board for all professional institutions, and the lack of monitoring and regulatory agencies for contractors and subcontractors within the industry. Oribuyaku (2015) and Ogunbiyi (2014) mentioned the lack of enforcement of the code in the literature.

Lack of 'Political will' by the government

A recurring issue emerging from the interviews was the perceived lack of political will on the part of the government to drive meaningful change within the Nigerian construction industry and the broader economy. While this concern is not prominently discussed in existing literature, it featured strongly in participants' narratives. Respondents emphasised that the absence of firm governmental commitment undermines policy implementation and contributes to systemic inertia. As one participant observed, *"It is the lack of political will to get things done that encourages corruption and a lukewarm attitude within the industry"* (Participant 2). Another noted that *"If the government wants something implemented, it gets implemented, and political will is essential to implementing policies in a democracy"* (Participant 6). These perspectives underscore the belief that the state's capacity to effect change is not limited by resources or technical constraints, but rather by a lack of sufficient resolve and continuity in governance.

The absence of sustained political will manifests in two critical ways for the construction sector. First, frequent changes in government officials and policy directions after election cycles often lead to the discontinuation or abandonment of existing plans and strategies. Consequently, initiatives related to sustainable construction rarely progress beyond the initial stages, as succeeding administrations may not share their predecessors' vision or priorities. This lack of continuity renders previous efforts moribund and interrupts long-term developmental agendas. Second, the findings underscore the importance of stronger industry–government collaboration in mitigating the effects of political transitions. Respondents suggested that collective industry action through professional bodies, councils, and advocacy platforms could help sustain policy momentum and ensure that sustainability goals outlive the typical four-year political cycle. Such collaboration could also foster accountability and policy consistency, both of which are essential for embedding sustainable practices within Nigeria's construction landscape.

4.3. Status of the building code

The interviews revealed a shared perception among participants that Nigeria's National Building Code is inactive and is applied inconsistently across the country. Respondents described the code as being in a "comatose state," with implementation limited primarily to a few urban centres such as Lagos and Abuja. This finding corroborates Ogunbiyi's (2014) observation that despite the existence of the code, its operationalisation remains weak due to inadequate enforcement mechanisms and institutional apathy.

Participants emphasised that while the building code exists in principle, its influence in regulating construction practice is negligible. As Participant 8 remarked, *"There may be Building Codes in Nigeria, but implementation is limited only to major projects and urban developments."* Similarly, Participant 4 noted that *"[It is] not adhered to because it is not a law. Resistance [exists] even from other relevant bodies within the industry (Planners and Architects)."* These insights underscore the perception that the code functions more as a guiding document than a binding legal instrument, which significantly limits its authority.

Several respondents attributed the code's poor implementation to its ambiguous legal standing and the lack of penalties for non-compliance. Participant 9 observed that *"The Nigerian Building Code is not actively implemented as projects are being constructed without approval and people tend to build anyhow and offenders go unpunished."* This lack of accountability reinforces a culture of impunity within the construction industry, where adherence to regulations becomes optional rather than mandatory. Echoing this sentiment, Participant 2 explained, *"Not many people know much about the building code until things happen, [then] people refer to it. Some think it is a guide, some think it is a law."* This confusion reflects both inadequate public awareness and weak institutional communication about the code's purpose and enforcement procedures.

Some respondents maintained that the code's introduction was a positive step but stressed that it remains at an early or "embryonic" stage of effectiveness. Participant 1 commented that it is *"At an embryo stage, as lack of legislation hinders [its implementation]. Not yet effective, but having it is a good step in the right direction."* Others expressed frustration that personal, professional, and institutional interests continue to hinder collective progress. As Participant 5 stated, *"The code is good but theoretical without the ability to act. Also, personal and professional interests hinder the implementation."* Participant 11 further expanded on this challenge, noting that *"As of now, the building code has many lapses. Some professionals (especially engineers) in the construction industry refused to adopt it because they felt they did not contribute to its content."*

These reflections highlight a critical issue in the construction industry: stakeholder disunity. Resistance among professional bodies—often rooted in jurisdictional disputes or feelings of exclusion from policy formulation—has impeded the development of a cohesive implementation strategy. As participants 4, 5, and 11 collectively implied, internal divisions and lack of synergy among architects, planners, engineers, and other professionals have weakened the code's legitimacy and enforceability. The findings therefore suggest that the challenge is not merely legislative but also relational, requiring improved inter-professional collaboration and participatory policy processes.

Therefore, while the existence of the Nigerian Building Code represents progress toward standardising construction practices, its limited enforcement, ambiguous legal status, and internal professional resistance have rendered it largely ineffective. Addressing these issues requires stronger legislative backing, public awareness campaigns, and coordinated stakeholder engagement to turn the code into an actionable framework that guides sustainable construction in Nigeria.

4.4. Improving sustainability in the Nigerian construction practice

The theme of improving sustainability in Nigerian construction practice was categorised into **governmental** and **professional** inputs, highlighting the shared responsibility of policymakers and practitioners in promoting sustainable construction. Participants collectively emphasised that achieving sustainability requires systemic reforms, consistent policy direction, professional competence, and the cultural integration of sustainability values.

Government inputs: The government's focus on sustainable construction must be clear and consistent, not subject to change with power shifts. Additionally, policies regarding tax subsidies, cost reduction, and import discouragement are primarily within the government's purview. "*Subsidies and reduced costs, discouraging importation and allowing local research and production to grow. Research aimed at commercial production by the Government.*" Participant 1. The government must also facilitate the growth of local research and production through commercialisation and promote cultural sustainability, which requires a serious, consistent approach. Awareness, training, and retraining of policy implementers within the industry, as well as a general orientation, are also needed on the part of the government to ensure sustainability is 'homegrown' within the industry.

Furthermore, sustainability must be embedded in cultural and educational frameworks. Participant 2 advocated that *"we need to make sustainability a way of life, culturally, teach it in schools. It requires a lot of seriousness and consistency."* This highlights the role of civic education in fostering long-term behavioural change.

Governmental efforts should also target education, awareness, and policy dissemination. Participants lamented the low public and professional awareness of sustainability-related policies, with Participant 4 observing that *"the publication of the existing policies [is limited]; most people do not know them—[there is a need for] general orientation."* This gap highlights the need for clear, accessible communication of government policies and for ongoing public engagement.

Professionals' inputs: While the government fosters an enabling environment, professionals and their institutions share equal responsibility for integrating sustainability into their daily practices. Participants emphasised that sustainable construction must begin at the design stage, integrating both passive and active design components. As Participant 1 explained, *"From design, active and passive components must be incorporated. Specifications and materials usage must be improved once the knowledge base of the professional increases."* This suggests that education and continuous professional development are prerequisites for sustainable design practice.

Concerns were also raised regarding the current level of professional competence in the industry. Participant 5 stated that *"the level of professionals in practice cannot lead us to sustainable construction because of inadequate training." At the same time,* Participant 3 reinforced that *"improvement in professional practice and artisanal training and improvement in material usage"* are needed. This reflects a skill gap not only among professionals but also within the artisanal workforce, as Participant 5 further asserted, *"Artisanal skills must be prioritised."* Strengthening vocational training would therefore enhance the quality and sustainability of construction output.

Moreover, participants called for stronger professional leadership and advocacy in the policy formulation process. As Participant 8 articulated, *"Professionals in the built industry should come up with appropriate laws and professionals should be trained on the benefits of inputting such."* This underscores the importance of co-producing regulatory frameworks that reflect both technical realities and sustainability imperatives.

Consistent with Bungwon et al.'s (2016) argument, participants highlighted local research and innovation as critical enablers of sustainability. Participant 1's call for *"Research and Development on improved and enhanced alternative building materials and development generally"* reflects a growing recognition that sustainable practices must be locally contextualised and grounded in indigenous knowledge systems.

4.5. The need for strict regulations and policies for SC practice

The participants were unanimous in affirming that strict regulations and enforceable policies are essential to drive sustainable construction (SC) practices within the Nigerian construction industry. The prevailing view was that without regulatory discipline and clearly defined consequences, efforts toward sustainability would remain ineffective. As Participant 2 emphasised, *"Yes, people must know there are consequences for their actions and inactions. People do things because they know they will get away with it. We need to be consistently strict."* This sentiment reflects a general perception that the lack of enforcement and accountability has long hindered the achievement of sustainability objectives in the sector.

Participants agreed that enforcement must be strengthened, not only to deter non-compliance but also to improve the overall quality of construction output. Participant 10 asserted, *"Yes, enforcement must be strict,"* while Participant 7 added that stricter regulatory controls *"will improve the quality of output in the industry."* Similarly, Participant 9 observed that *"People fear the law and only tend to respect the authority,"* suggesting that consistent, transparent law enforcement could serve as an effective behavioural driver of compliance. This corroborates earlier observations by Ogunbiyi (2014), who linked regulatory weaknesses and poor enforcement mechanisms to the prevalence of substandard practices in the Nigerian construction sector.

However, participants also cautioned that strict regulations should be implemented in a phased, inclusive manner. Participant 1 suggested that *"Before we get to strict policy, we need to teach. It is a process,"* highlighting the need for preparatory capacity-building and stakeholder sensitisation before enforcement begins. Similarly, Participant 8 supported this position by stating, *"Yes, but there is a need for stakeholders to be educated,"* reinforcing the importance of public and professional education as a foundation for policy legitimacy and effective implementation. This aligns with the argument by Bungwon et al. (2016), who noted that sustainable policy outcomes depend on the extent to which affected stakeholders are informed and aligned with policy objectives.

Overall, the data suggest that regulatory reform must strike a balance between firmness and fairness, ensuring that rules are not only punitive but also educative and enabling. Participants consistently called for clear, consistent, and enforceable frameworks that would compel compliance across all levels of practice while maintaining fairness and transparency. As Participant 9 succinctly remarked, *"Very well, that is the key,"* underscoring the consensus that robust and well-enforced regulations are fundamental to achieving a more sustainable and accountable construction industry.

The findings from this theme suggest that stringent regulations and policies are essential for promoting sustainable construction practices in Nigeria. However, their success depends on complementary measures such as stakeholder education, phased implementation, and institutional support. The participants' views highlight an urgent need for a well-coordinated regulatory framework—one that enforces compliance while promoting understanding, capacity development, and cultural acceptance of sustainability principles within the construction ecosystem.

4.6. Input of stakeholders to drive sustainability

The contributions expected from stakeholders to drive sustainability in the Nigerian construction industry are depicted in Figure 2.

Professional Institutes and Professionals

Professionals must uphold high standards in their practices and provide clients with well-informed advice. Additionally, interdisciplinary research within the industry and firmer collaboration among professionals are encouraged. Professional institutes must take greater responsibility by engaging in research, increasing public awareness, and fostering synergy among fellow professional bodies.

Government as a Stakeholder

The government plays a critical role in shaping industry policy, as emphasised in the literature (Akadiri et al., 2012; Ojo et al., 2014). Raising awareness and

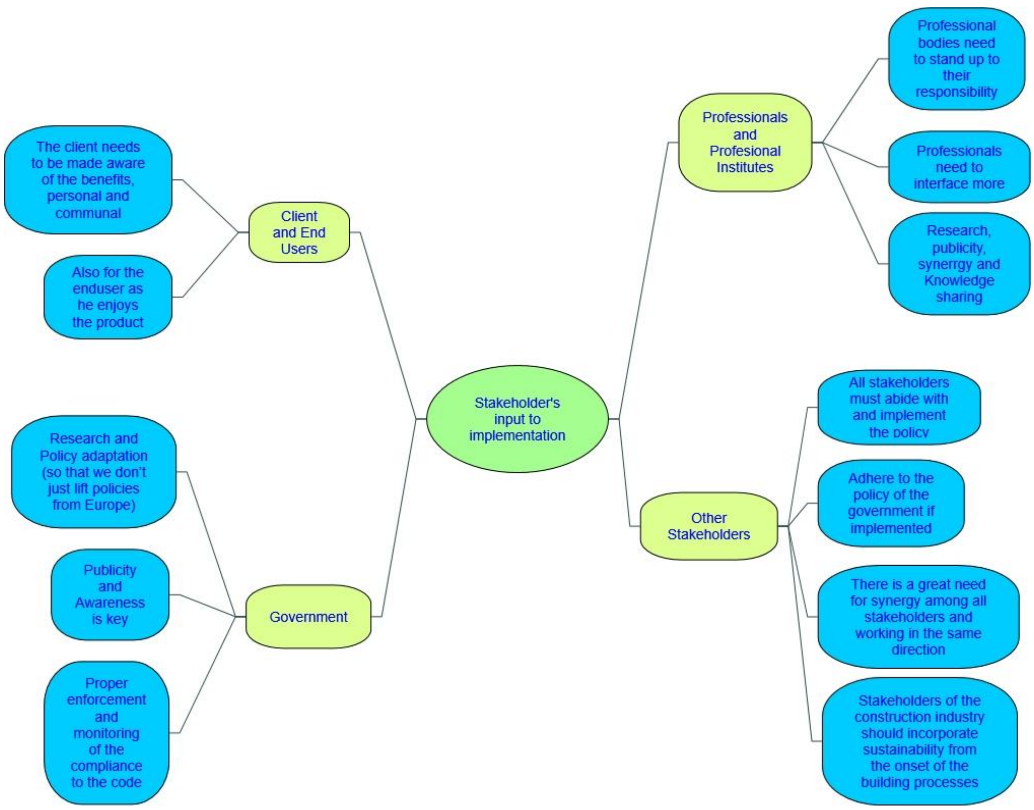

Figure 2: Sub-theme on stakeholders' input to sustainable construction implementation

increasing publicity efforts are essential, as contractors and other industry practitioners look to the government for guidance and patronage. Furthermore, investment in research and development is necessary to ensure effective policy adaptation. As noted *by Participant 4, this will prevent situations in which "policies are not just lifted from Europe and other developed nations*" without proper consideration of Nigeria's unique context.

Clients and End-Users

Clients must be informed about the benefits of sustainable construction, specifically how it affects their quality of life and overall comfort. Greater awareness is expected to influence client demands, which, in turn, will shape construction outputs.

Other Stakeholders

Actors such as developers must comply with industry minimum standards and regulations throughout all stages of construction. Coordination among all industry players is crucial to achieving sustainability goals. However, as Participant 6 observed, "*Developers in the Nigerian construction industry are mostly profit-driven and, as such, have reserved regard for quality delivery*."

4.7. Implementation of Sustainable construction through the municipality

Participants widely acknowledged the role of local government in advancing sustainable construction (SC) as both strategic and necessary. Consistent with Davies and Davies (2017), respondents agreed that local governments are best positioned as the starting point for implementing sustainable construction policies because they are geographically closer to the people and operate across all regions of the country. Participant 4 emphasised this proximity advantage by stating that *"They are not active. The LG should be as they are closer to the people,"* while Participant 3 similarly observed that *"They have not been active, and more can be done… They can be the needed agent as they are closer to the people."* This perspective aligns with Nwokoro and Onukwube (2015) and Tunji-Olayeni et al. (2018), who argue that, if empowered, local authorities can play a pivotal role in ensuring the enforcement of sustainability standards within the built environment.

However, participants raised serious concerns regarding the capacity and integrity of local governments to take on this role effectively. Many respondents noted that local authorities currently lack the institutional strength, manpower, and motivation to drive sustainable construction initiatives. As Participant 1 remarked, *"The local government is best suited, but the capacity could be a challenge right now." At the same time,* Participant 2 added, *"Yes, if the local level can be active, it will greatly reduce the negative effects at the federal level, but it is currently the weakest unit of government."* This sentiment reflects widespread scepticism about the local government's readiness to lead implementation efforts, given its existing inefficiencies.

Beyond capacity issues, corruption and weak accountability were repeatedly cited as significant impediments. Participant 11 commented that *"They are corrupt; they compromise easily. They are also not adequately motivated to carry out the enforcement. They are poorly remunerated, so they are exposed to the temptation of bribery and corruption."* Similarly, Participant 8 noted, *"Yes. The LG is not empowered, though,"* implying that without greater institutional support and oversight, local governments are unlikely to execute sustainability policies effectively. These concerns echo earlier findings by Ogunbiyi (2014), who identified systemic corruption and lack of enforcement as significant barriers to construction reform in Nigeria.

Despite these challenges, respondents maintained that empowering municipalities remains a viable pathway for improving sustainable construction, provided that institutional reforms and capacity-building measures are prioritised. Participant 7 encapsulated this by stating, *"They need more improvement. Government must ensure their active participation, compliance being at the grassroots."* This reflects the belief that the success of sustainability initiatives depends on grassroots enforcement, where local governments act as the interface between policy and practice. Strengthening their administrative and technical capacity through training, resource allocation, and improved remuneration was identified as a critical step towards achieving this goal.

While participants recognised the municipality as an essential platform for implementing sustainable construction, they stressed that its effectiveness is currently undermined by inadequate capacity, corruption, and a lack of empowerment. To address these limitations, national and state governments must invest in institutional reforms that enable local authorities to operate transparently and efficiently. Only through such deliberate empowerment can municipalities transform from passive entities into active agents of sustainable construction, capable of translating policy intentions into tangible environmental and social outcomes.

5. Conclusion and Recommendations

This study examined the policy challenges hindering the implementation of sustainable construction (SC) in the Nigerian construction industry. Drawing on perspectives from experienced professionals across multiple built-environment disciplines, the study found that sustainability practice remains weak, fragmented, and inconsistent across the sector. The findings confirm a persistent policy implementation gap driven by weak regulatory enforcement, an inactive national building code, insufficient inter-professional collaboration, a lack of local institutional capacity, and insufficient political will at different levels of government.

A key implication of these findings is that sustainable construction will not become mainstream in Nigeria without stronger state leadership. Government, as both regulator and major client, occupies a central role in shaping industry behaviour and signalling national priorities. Participants consistently noted that the lack of enforcement mechanisms has allowed widespread non-compliance to continue unchecked, particularly at the local government level. Policy discontinuity linked to political transitions further disrupts momentum, weakening confidence in long-term sustainability reforms.

A related insight concerns the need for stronger institutional collaboration. The study highlights that professional bodies and regulatory institutions currently act in silos, limiting their influence on policy design and implementation. The absence of a unified technical voice has also slowed the development of coherent sustainability standards, rating systems, and skills development pathways. Strengthening cross-disciplinary collaboration—especially among architects, engineers, quantity surveyors and builders—is therefore critical for embedding sustainability practices at the project and policy level.

Prioritised Practical Recommendations

Based on the findings, four priority actions are recommended:

1. Legal empowerment and enforcement of the Nigerian Building Code.

2. The code should be fully legislated, regularly updated, and supported by compulsory compliance checks. Statutory sanctions for non-compliance are essential to reduce building failures and incentivise sustainable practices.

3. Capacity-building and anti-corruption mechanisms at the municipal level.

4. Local governments require targeted training programmes, staffing upgrades, monitoring systems, and transparent enforcement procedures to reduce corruption and improve planning control—especially since SC implementation occurs at project approval and inspection stages.

5. Institutionalised interdisciplinary collaboration. Professional bodies should create a unified sustainability platform that aligns technical standards, skill development, and advisory roles. Joint advocacy and shared agendas will enhance industry influence in national policy and foster stronger public–private cooperation.

6. Strategic awareness and education programmes. Professional training, public sensitisation, and media campaigns are needed to build a shared understanding of sustainable construction, improve acceptance of new regulations, and support the long-term cultural shift required for SC adoption.

Collectively, these recommendations provide a realistic pathway for embedding sustainability into Nigeria's construction environment and align with the research aim of identifying policy conditions necessary for effective SC implementation.

Limitations of the Study

This research is geographically limited to Abuja and Lagos—two major urban centres with high concentrations of professionals. These contexts may not fully represent the experiences of practitioners in other regions with different institutional and economic conditions. Furthermore, the purposive sampling strategy, which targeted professionals experienced in sustainability and policy environments, restricts generalisability. Nevertheless, these samples enabled the study to capture rich expert insight into the core research problem, supporting analytical rather than statistical generalisation.

Contribution to Knowledge

This study contributes to knowledge by advancing empirical understanding of why sustainable construction policy has struggled to gain traction in Nigeria. It provides evidence from industry practitioners that reinforces the conceptual argument introduced in the paper: institutional weaknesses, enforcement failures, and governance constraints—not merely technical barriers—constitute the most significant obstacles to SC adoption.

The study also fills a regional knowledge gap by connecting sustainability debates to real policy processes rather than conceptual ideals. It demonstrates that stronger inter-professional collaboration, political commitment, and municipal empowerment are critical determinants of implementation success in developing-country contexts. These insights extend the literature beyond Nigeria, offering a transferable framework for other emerging economies facing similar policy and governance limitations.

Sustainable construction in Nigeria will only advance through coordinated, long-term commitment built on strong regulatory authority, empowered local enforcement structures, and a cohesive professional community. By illustrating how political will, implementation capacity, and institutional cooperation shape sustainability outcomes, this study provides a platform for future research and policymaking to transition Nigeria's built environment toward global best practices.

References

Akinyemi, A. P., Adekunle, A. O., Joseph, O. O., Anthony, A. I., & Dabara, D. I. (2017). The need for green building rating systems development in Nigeria: The process, progress, and prospects. *Academic Journal of Science, 9*(2), 35–44.

Akadiri, P. O., Chinyio, E. A., & Olomolaiye, P. O. (2012). Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. *Buildings, 2*(2), 126–152.

Atanda, J. O., & Olukoya, O. A. (2019). Green building standards: Opportunities for Nigeria. *Journal of Cleaner Production, 227*, 366–377.

Babalola, A., & Harinarain, N. (2024). Policy barriers to sustainable construction practice in the Nigerian construction industry: An exploratory factor analysis. *Journal of Engineering, Design and Technology, 22*(1), 214–234. https://doi.org/10.1108/JEDT-07-2021-0375

Bungwon, H. D., Dabo, D. I., & Ishaya, D. A. (2016). A study of the awareness of property managers and other built environment professionals on sustainable buildings in Kaduna, Nigeria. *International Journal of Research in Chemical, Metallurgical and Civil Engineering, 3*, 94–96.

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry & research design: Choosing among five approaches* (4th ed.). SAGE

Davies, O., & Davies, I. (2017). Barriers to implementation of sustainable construction techniques. *Journal of Environmental Science, 2*, 1–9.

Drysdale, D., Mathiesen, B. V., & Paardekooper, S. (2019). Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. *Energy Efficiency*, *12*(1), 37-55. https://doi.org/10.1007/s12053-018-9649-1

Federal Republic of Nigeria. (2006). *The Nigerian building code*. Alexis Nexus, Butterworths Publications.

Geissler, S., Österreicher, D., & Macharm, E. (2018). Transition towards energy efficiency: Developing the Nigerian building energy efficiency code. *Sustainability, 10*(8), 2620.

Gibbs, D., & O'Neill, K. (2015). Building a green economy? Sustainability transitions in the UK building sector. *Geoforum, 59*, 133–141.

Goh, C. S., Jack, L., & Bajracharya, A. (2020). Qualitative study of sustainability policies and guidelines in the built environment. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 12*(2). https://doi.org/10.1061/(ASCE)LA.1943-4170.000039

Heijden, J. & Bueren, E. (2013). Regulating Sustainable Construction in Europe: An Inquiry into the European Commission's Harmonisation Attempts (July 17, 2013). The International Journal of Law in the Built Environment, 5(1). http://dx.doi.org/10.2139/ssrn.2294820.

Hennink, M. & Kaiser, B.N. (2022). Sample sizes for saturation in qualitative research: A systematic review of empirical tests. Social Science & Medicine, 292, 114523. https://doi.org/10.1016/j.socscimed.2021.114523.

Hill, M. J., & Hupe, P. L. (2014). *Implementing public policy: An introduction to the study of operational governance* (3rd ed.). Sage.

Hudson, B., Hunter, D., & Peckham, S. (2019). Policy failure and the policy–implementation gap: Can policy support programs help? *Policy Design and Practice, 2*(1), 1–14.

Isang, I. W. (2023). A historical review of sustainable construction in Nigeria: A decade of development and progression. *Frontiers in Engineering and Built Environment, 3*(3), 206–218. https://doi.org/10.1108/FEBE-02-2023-0010

Nwokoro, I., & Onukwube, H. (2015). Understanding green and sustainable construction in Lagos, Nigeria: Principles, attributes and framework. *Ethiopian Journal of Environmental Studies and Management, 8*(1), 57–68.

Ogunbiyi, M. A. (2014). The National Building Code and construction industry professionals in Nigeria. *International Journal of Social Sciences and Entrepreneurship, 1*(12), 937–948.

Ojo, E., Mbowa, C., & Akinlabi, E. T. (2014). Barriers to implementing green supply chain management in the construction industry. In the *International Conference on Industrial Engineering and Operations Management*.

Onuoha, I. J., Kamarudin, N., Aliagha, G. U., Okeahialam, S. A., Atilola, M. I., & Atamamen, F. O. (2017). Developing policies and programmes for green buildings: What can Nigeria learn from Malaysia's experience? *International Journal of Real Estate Studies, 11*(2), 50–58.

Oribuyaku, D. (2015). Code for a sustainable built environment in Nigeria: A proposed high-level vision of a policy framework. *Construction Management and Economics*, 2–10.

Oyewobi, L. O., & Jimoh, R. A. (2022). Barriers to the adoption of sustainable procurement in the Nigerian public construction sector. *Sustainability, 14*(22), 14832. https://doi.org/10.3390/su142214832

Scott, W. R. (2014). Institutions and Organisations: Ideas, Interests, and Identities (4th ed.). Thousand Oaks, CA: Sage Publishing.

Solanke, B., & Fapohunda, J. A. (2016). Strategies for effective materials management in sustainable construction enhancement. In *CIDB Postgraduate Conference* (Vol. 3, pp. 496–505). Cape Town, South Africa.

Tracy, S. J. (2012). *Qualitative research methods: Collecting evidence, crafting analysis, communicating impact*. John Wiley & Sons.

Tunji-Olayeni, P. F., Mosaku, T. O., Oyeyipo, O. O., & Afolabi, A. O. (2018, May). Sustainability strategies in the construction industry: Implications for green growth in Nigeria. In *IOP Conference Series: Earth and Environmental Science* (Vol. 146, No. 1, Article 012004).

World Green Building Council. (2020). *Our green building councils*. https://www.worldgbc.org/member-directory.

Appendix 1

Table 1: The demographic details of the participants

Interviewee	Profession	Age	Gender	Qualification	Years of Experience	Place of work
Participant 1	Architect	>50	Male	Masters, PMP, FNIA	30	Federal Govt. Agency, Abuja
Participant 2	Architect	>50	Male	Masters, MBA, FNIA	25	Private Practice, Abuja
Participant 3	Civil Engineer	45 -50	Male	MSc, MNSE	30	Govt. Agency
Participant 4	Builder	45- 50	Male	MSc, FNIOB	30	Building Control Agency, Abuja
Participant 5	Quantity Surveyor	40-45	Male	MSc, FNIQS	20	Govt Agency, Abuja
Participant 6	Quantity Surveyor	40-45	Male	MSc, MNIQS	15	Private Practice, Abuja
Participant 7	Builder	35-40	Male	MSc, MNIOB	13	Private Practice, Lagos
Participant 8	Civil Engineer	45-50	Male	BSc, MNSE,	20	Private Practice, Lagos
Participant 9	Urban Planner	35-40	Female	BSc, MNITP	15	Local Govt. Municipal office in Lagos
Participant 10	Quantity Surveyor & Lecturer	50-55	Male	PhD, MNIQS	21	Private Practice & Academic
Participant 11	Quantity Surveyor	45-50	Female	MSc, MNIQS, PMP	24	Project Mgt Firm

- FNIA - Fellow of the Nigerian Institute of Architects.
- MNIOB - Member, Nigerian Institute of Building,
- MNIQS - Nigerian Institute of Quantity Surveyors for the quantity surveyors.
- MNSE - Nigerian Society of Engineers,
- MNITP - Nigerian Society of Urban (town) planners.

JCBM (2025) 8(S1) 125-139

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

From Exploration to Prioritisation: Advancing BIM-IOT Integration for Construction Health and Safety Improvement

Mojtaba Amiri[1] and Ehsan Saghatforoush[2]

[1&2]Construction Economics and Management, Engineering and the Built Environment, University of the Witwatersrand, South Africa

Received 12 October 2025; received in revised form 14 October 2025, 25 December 2025; accepted 28 December 2025
https://doi.org/10.15641/jcbm.8.S1.1939

Abstract

The construction industry faces significant workplace safety-related challenges, with developing countries experiencing disproportionately high accident rates. While Building Information Modelling (BIM) and the Internet of Things (IoT) technologies show individual promise for enhancing safety, their integrated application remains underexplored in developing contexts. This study employs a mixed-methods approach combining a systematic literature review with quantitative survey validation to investigate the advantages of BIM-IoT integration for construction safety in South Africa. The literature review analysed peer-reviewed articles published between 2010 and 2025, while the empirical phase surveyed 252 South African construction professionals using a structured questionnaire. Statistical analysis employed exploratory and confirmatory factor analysis (EFA/CFA) using SPSS and AMOS to validate identified advantages. The systematic review identified 15 key advantages, with "improved safety monitoring" as the most cited, followed by "real-time decision-making" and "hazard identification". Quantitative validation confirmed strong alignment between the literature and practice, with the same three advantages ranking highest among practitioners (mean scores of 4.28, 4.22, and 4.19, respectively), confirming the universal applicability of the core advantages. Exploratory factor analysis identified five latent dimensions, accounting for 67.8% of the total variance: Real-time Monitoring & Control, Safety Planning & Design, Training & Communication, Investigation & Reporting, and Compliance & Economics. Confirmatory factor analysis validated the measurement model with strong fit indices (CFI > 0.90, RMSEA < 0.08), and all constructs showed high reliability (Cronbach's $\alpha > 0.70$). Context-specific insights revealed that South African professionals prioritise regulatory compliance and cost considerations more than global literature suggests, while design-phase hazard elimination ranked lowest despite theoretical recognition. Despite moderate BIM familiarity (3.42) and low IoT familiarity (2.89), only 34.6% and 23.7% of companies have implemented these technologies, respectively, indicating substantial implementation gaps beyond awareness. This research provides comprehensive quantitative validation of BIM-IoT safety advantages in a developing country context, offering evidence-based priorities for technology adoption and policy development.

Keywords: Advantages, BIM-IoT, Integration, Construction Safety, South Africa

1. Introduction

Workplace safety has become a critical priority for industries due to its profound impact on employee health and overall productivity, with the construction industry experiencing a disproportionately high rate of workplace accidents (Kim and Chi, 2019). Occupational hazards are a persistent challenge in construction (Heidary Dahooie et al., 2020), as frequent accidents not only diminish workforce efficiency but also increase absenteeism. In South Africa, this challenge is particularly acute, with the construction industry recording 17.5 workplace fatalities per 100,000 workers annually and over 150 deaths in 2022 alone (Department of Employment and Labour, 2022; CIDB, 2022). Given the significantly higher accident frequency in construction compared to other industries, this sector faces heightened safety risks (Nadhim et al., 2016).

Integration of Digital technologies capable of analysing and effectively communicating safety issues is crucial

[1] Corresponding Author
Email address: mojtaba.amiri@wits.ac.za

for improving overall safety performance (Han et al., 2009). In the past decade, research has focused on using digital technologies to reduce health and safety risks on construction sites. Key advancements include computer vision, IoT sensors, wearable devices, BIM, and immersive technologies like augmented and virtual reality, all aimed at improving hazard detection and safety management (Zhang et al., 2017). Despite advancements, single-technology solutions fall short of optimal safety standards, and research shows that a multi-technology approach integrating various tools yields more reliable safety outcomes (Wang et al., 2021). Integrating BIM with real-time data from IoT devices enhances construction safety by linking IoT sensor networks to high-fidelity BIM models, enabling various applications (Tang et al., 2019).

In recent years, various studies have explored the application of BIM-IoT integration in safety management (Amiri et al., 2024); however, there is a lack of research that identifies and analyses the advantages of adopting BIM and IoT technologies to improve safety in the construction sector. Specifically, while qualitative studies have identified potential advantages, quantitative validation of these advantages using empirical data from developing countries like South Africa remains limited.

The key question is: "What are the advantages of BIM-IoT integration in construction health and safety, and how can these advantages be quantitatively validated in the South African construction context?" This study has two main objectives: first, to systematically identify and synthesise the advantages of BIM-IoT integration for construction health and safety through a structured literature review; and second, to empirically validate and model these advantages- conceptualised as five dimensions of real-time monitoring and control, safety planning and design, training and communication, investigation and reporting, and compliance and economics- using survey data from South African construction professionals.

2. Literature Review

Adoption of digital technologies in construction projects has grown due to the numerous benefits they offer in enhancing safety on construction sites. According to Luo et al. (2022), there is a growing trend in research utilising digital technologies to improve construction safety, with Virtual Reality, Augmented Reality, Digital Twins, BIM, and the IoT identified as the most effective technologies. While BIM and IoT have been applied in areas such as health and safety management, research on their integration is still in its early stages (Dave et al., 2018).

2.1. BIM and Construction Safety

Recent studies have shown that implementing the BIM methodology can improve the working conditions at construction sites (Cortés-Pérez et al., 2020). Azhar (2017) found that BIM can be utilised for better construction safety performance. BIM, a growing digital technology, is gaining attention for its role in enhancing safety design and improving construction safety management practices due to its object-oriented nature and effectiveness (Jin et al., 2019; Ding et al., 2014). Based on the literature reviewed, the main application of BIM in the safety management of the construction industry can be summarised into three areas: interactive worker training, site layout optimisation, and automated checks for safety issues (Chatzimichailidou and Ma, 2022).

Several studies have investigated the use of BIM in managing construction safety issues. A classification of BIM-based tools highlighted the use of Virtual Reality to enhance construction safety, particularly in training activities (Getulli et al., 2018). Another review compared BIM-based approaches with traditional risk management tools, emphasising BIM's potential in risk management, although it lacked a systematic selection of research published after 2015 (Zou et al., 2017). Research on the use of BIM and related technologies in the design phase focused on improving safety management and minimising design errors, with particular attention to Design for Safety (DfS) and its barriers (Xiaer et al., 2016). An investigation into BIM's shortcomings and its impact on safety involved a survey of field engineers in the construction industry (Alomari et al., 2017). Lastly, the relationship between BIM and worker safety performance was examined by identifying key factors and barriers through a literature review and a practitioner survey (Ganah and Godfaurd, 2015).

2.2. IOT and Construction Safety

IoT has demonstrated significant potential in high-risk Environment, Health, and Safety (EHS) industries, where human lives are at stake, offering safe, reliable, and efficient solutions through fine-grained operation and rich data collection (Wang et al., 2021). In construction, IoT automates safety monitoring and hazard detection, enabling connected devices to transfer and analyse data effectively, making it a suitable technology for facilitating seamless data transmission across systems (Tabatabaee et al., 2022). Several studies have investigated the use of IoT in managing construction safety issues. Yang et al. (2020) developed a tool based on IoT for detecting Personal Protective Equipment (PPE) to ensure that workers are provided with the appropriate PPE before beginning construction activities. Additionally, Kanan et al. (2018) created a protective IoT-based system to automatically monitor, localise, and warn construction workers in hazardous areas.

A detailed evaluation of the LoRa protocol demonstrated its suitability for IoT-based safety monitoring, provided battery-related constraints are addressed (Augustin et al., 2016). A Wi-Fi-based IoT safety surveillance system was proposed to connect field devices, such as cameras and smoke detectors, offering an innovative safety solution despite challenges in power supply and mobility (Jiang et al., 2013). Computer vision-based wireless sensing technology monitored workers' compliance with personal protective equipment (Park and Brilakis, 2012), while motion tracking systems detected unsafe postures to reduce musculoskeletal risks (Ray and Teizer, 2012; Seo et al., 2013).

2.3. BIM-IoT Integration

Over the past decade, the integration of BIM and IoT has attracted growing interest, as evidenced by a steady increase in scholarly publications on the topic. These technologies offer complementary strengths: BIM provides detailed, component-level visualisations of construction projects, while IoT enhances safety management by supplying real-time data on-site conditions (Mohd-Nor et al., 2019). By combining these capabilities, BIM-IoT integration supports data-driven decision-making and more proactive safety interventions (Mohammed et al., 2020).

2.3.1. BIM-IoT integration and construction safety

According to Tang et al. (2019), prevalent applications integrating BIM and IoT data for health and safety management include safety training and on-site monitoring. Numerous studies have explored BIM-IoT integration for managing construction safety, highlighting its potential to enhance hazard identification, real-time monitoring, and overall safety performance.

Li et al. (2015) developed the Proactive Construction Management System (PCMS) for real-time safety monitoring and feedback, improving safety awareness and efficiency on a Hong Kong site and demonstrating global applicability for workforce training. Riaz et al. (2014) developed a BIM and sensor-based safety monitoring solution for confined spaces. Cheng and Teizer (2013) developed a framework to stream real-time data to a VR platform to improve safety awareness. Kanan et al. (2018) introduced an IoT-based wearable system to provide real-time hazard alerts on construction sites. Ding et al. (2022) implemented an IoT-BIM system to manage hazardous energy on construction sites. Qian (2021) developed a tunnel monitoring system combining BIM, IoT, and GNSS to enhance safety and construction management. Kim et al. (2016) developed a BIM-based automated safety system to address scaffolding hazards by simulating worker movements and identifying potential risks. The system, integrated into commercial BIM software, successfully detected hazards and improved early safety communication in a real-world project. Scianna et al. (2022) integrated IoT sensors with BIM for real-time bridge deflection monitoring, linking the physical structure to its digital twin for continuous risk assessment.

3. Research Methodology

This study employs a mixed-methods research approach, combining a systematic literature review (SLR) with empirical survey validation, to provide comprehensive insights into the advantages of BIM-IoT integration. The SLR identifies and synthesises existing knowledge, while the quantitative survey validates these findings using data from South African construction professionals.

3.1. Phase 1: Systematic Literature Review

A Systematic Literature Review (SLR) synthesises past research through a structured process to identify key themes, gaps, and future research areas while minimising bias and ensuring consistency (Zhou et al., 2015). This study employs an SLR to examine BIM-IoT integration for construction safety management, following a seven-step approach (Figure 1).

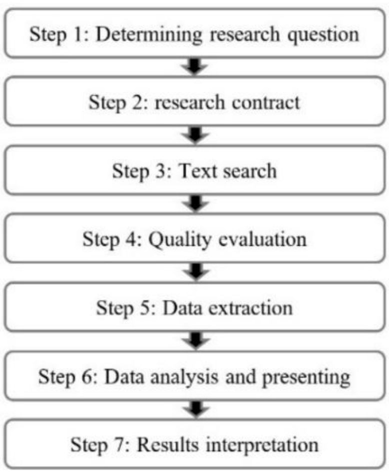

Figure 1: The SLR steps (Wright et al., 2007)

To ensure reproducibility, the SLR focused on peer-reviewed journal articles published between 2010 and 2025, written in English, and explicitly addressing BIM-IoT integration for construction health and safety. Articles were retrieved from three major databases-ScienceDirect, Scopus, and Web of Science (WoS) Core Collection-using combinations of the keywords "BIM", "IoT", "safety", and "advantages/benefits". The inclusion and exclusion criteria are summarised in Table 1, while the distribution of articles across databases is presented in Table 2.

Table 1: The criteria for inclusions and exclusions

Criteria	Inclusions	Exclusions
Publication timeline	• Between 2010 and 2025	• Before 2010
Document type	• Peer-reviewed journal research articles	• Books, book chapters, reports, theses, conference papers, editorials
Type of domain	• BIM-IOT integration in safety management only	• BIM-IOT integration in other domains (e.g. Facility management) and single-technology studies without integration
Language	• English	• Non-English

Table 2: BIM-IOT initial search results

Databases	Science direct		Scopus		Web of Science	
Search BIM-IOT	Total articles	Selected articles	Total articles	Selected articles	Total articles	Selected articles
Numbers	315	142	124	32	103	24

In Step 1, the research question is defined to establish scope and relevance, ensuring a balanced focus (Glasziou et al., 2001). In Step 2, an SLR protocol is developed to provide a structured selection process that covers the background, research question, and strategy (Henderson et al., 2010). In Step 3, a comprehensive literature search is conducted, using defined search terms and strict inclusion/exclusion criteria to ensure consistency (Wright et al., 2007). In Step 4, selected studies are evaluated using the CASP checklist to assess quality and relevance. In Step 5, data extraction is carried out using tailored forms to avoid duplicates, with a two-stage screening of titles, abstracts, and key sections. In Step 6, data analysis groups key findings by similarities in BIM-IoT integration for construction safety across design and construction. Finally, in Step 7, the results are presented through descriptive analysis, categorising text data to reveal patterns, and pattern coding, identifying themes to refine insights and develop a theoretical framework (Saldaña, 2021; Miles & Whitehouse, 2013).

3.2. Phase 2: Quantitative Validation Survey

While the systematic literature review successfully identified key advantages of BIM-IoT integration, this study extends the methodology through a quantitative validation phase to provide empirical evidence from the South African construction context. This approach enhances the reliability and generalizability of findings by combining qualitative synthesis with statistical validation.

3.2.1. Research design

A cross-sectional survey design was adopted to validate the identified advantages and explore implementation factors specific to the South African construction industry. This approach allows for the collection of standardised data across different construction organisations while maintaining the statistical rigour necessary for factor analysis and structural equation modelling.

3.2.2 Questionnaire Development

The survey instrument was developed based on the 15 advantages identified through the SLR (Appendix 1). Each advantage was operationalised into multiple measurement items using established scales from technology acceptance and construction safety literature. The questionnaire comprised five main sections:

Section A: Demographics - Participant and organisational characteristics, including age, experience, education, company type, size, and CIDB grading.

Section B: Technology Familiarity - Current knowledge and experience with BIM and IoT technologies using 5-point Likert scales.

Section C: Benefit Assessment - Evaluation of each identified advantage across three dimensions: importance for projects, potential safety impact, and implementation likelihood (5-point scales: 1=strongly disagree to 5=strongly agree).

Section D: Implementation Context - Assessment of organisational readiness and success factors.

Section E: Open-ended Questions - Qualitative insights on specific safety challenges and additional advantages.

The questionnaire underwent content validation by three construction technology experts and pilot testing with 35 industry professionals to ensure clarity and relevance.

3.2.3 Sampling strategy

The target population comprised construction professionals from companies registered with the Construction Industry Development Board (CIDB) at Grades 4-7, representing contractors capable of implementing advanced technologies. Using Cochran's formula with a 95% confidence level and 5% margin of error, a minimum sample size of 252 was calculated.

A stratified sampling approach was employed based on:

- **Geographic distribution:** 60% Gauteng Province, 20% Western Cape, 10% KwaZulu-Natal, 10% other provinces
- **Company size:** 40% Small (5-50 employees), 35% Medium (51-200), 25% Large (200+)
- **CIDB grading:** Proportional representation across Grades 4-7

3.2.4 Data collection procedure

Data collection was conducted using an online survey platform distributed via email, professional networks, and industry conferences to CIDB-registered contractors. This study received ethics approval from the University of Witwatersrand Research Ethics Committee (Approval No: H25/07/02). Informed consent was obtained from all participants. Participation was voluntary and anonymous, with responses stored securely and reported in aggregate form to ensure confidentiality. Average completion time was 15-20 minutes.

3.2.5 Statistical analysis plan

Data analysis followed a systematic approach using SPSS v29 and AMOS v29:

- **Phase 1: Descriptive Analysis -** Frequency distributions, descriptive statistics, and normality testing
- **Phase 2: Exploratory Factor Analysis (EFA)** - Kaiser-Meyer-Olkin measure (>0.7), Bartlett's test, Principal component analysis with Varimax rotation
- **Phase 3: Confirmatory Factor Analysis (CFA)** - Assessment of measurement model fit using multiple indices (χ^2/df < 3.0, CFI > 0.9, RMSEA < 0.08)
- **Phase 4: Reliability and Validity Assessment** - Internal consistency (Cronbach's α > 0.7), convergent validity (AVE > 0.5), discriminant validity

This study focused on validating the measurement model through EFA and CFA. Structural Equation Modelling (SEM) is recommended for testing hypothetical relationships between factors and adoption outcomes in future research. The quantitative findings are integrated with the SLR results to provide comprehensive insights into the advantages of BIM-IoT for construction safety management in the South African context.

4. Findings and Results

4.1. Systematic Literature Review finding

To identify the advantages of BIM-IoT integration in construction health and safety, the systematic review steps are applied as follows.

Step 1: Determining research questions

- "What are the advantages of BIM-IoT integration in construction health and safety?"

Step 2: research contract

The protocol developed to guide the selection of studies used in this research includes the following steps:

- Background

Since the research explores BIM-IoT integration in construction safety and its advantages, this foundation informs the inclusion and exclusion criteria in the review protocol.

- Research question

The overarching objective of conducting an SLR is to address the following question:

"What are the advantages of BIM-IoT integration in construction health and safety?"

- Research strategy and data sources

To identify the most relevant answers to the research question, the strategy outlined in Figure 2 is applied throughout the SLR process.

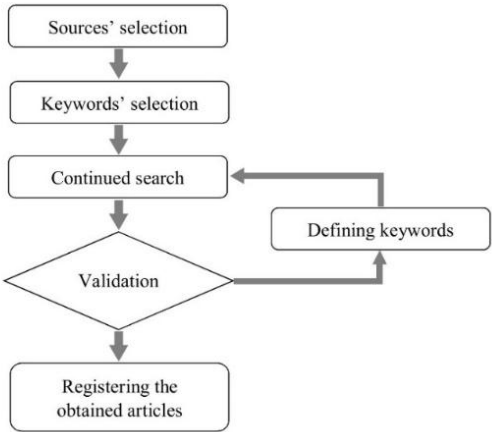

Figure 2: Research strategy

The keywords for the SLR were derived from the research question, focusing on "BIM", "IoT", "safety", and "construction". The following Boolean search strings were executed across three major indexed databases (ScienceDirect, Scopus, and Web of Science Core Collection):

[("BIM" OR "Building Information Modelling" OR "Building Information Modelling")
AND ("IoT" OR "Internet of Things" OR "Internet of Things")
AND ("safety" OR "health and safety" OR "OSH" OR "occupational safety" OR "workplace safety")
AND ("construction" OR "building" OR "construction site")]

Step 3: Text search

The authors utilised the following input and output criteria to select articles for the SLR, as illustrated in Table 1.

The search, conducted from August 2024 to January 2025 using keywords, yielded 542 articles (315 from ScienceDirect, 124 from Scopus, and 103 from WoS). After removing duplicates and irrelevant studies, 198 articles remained (Table 2).

At this stage, 198 papers were reviewed based on keywords, abstracts, and full texts, resulting in the selection of 94 articles (Table 3).

Step 4: Quality evaluation

In this section, the codes are classified as outlined in the results presentation step (Figure 3).

The final evaluation used the CASP instrument, which assessed 10 criteria, including research design and methodology. Articles were rated on a 5-point scale and categorised into quality groups. The qualitative scores

Table 3: Keywords and reviewing abstracts

Databases	Science direct	Scopus	Web of Science
Search keywords	51	20	23
Final selected articles	94		

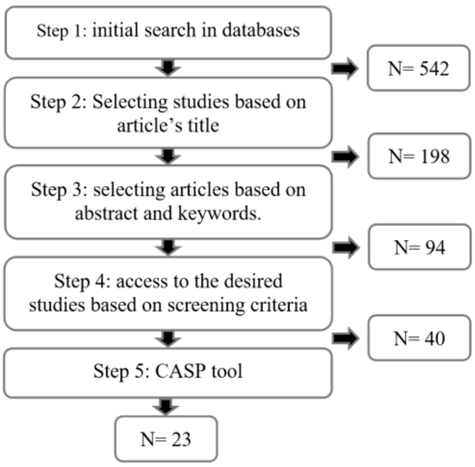

Figure 3: Steps for selection of the articles

were then categorised into very good (41-50), good (31-40), medium (21-30), poor (11-20), and very poor (0-10). Those scoring below 20 were excluded, leaving 23 articles for analysis.

Steps 5 and 6: Data extraction and Data analysis
To extract relevant data, the following questions guide the data extraction process:

- Does the article address BIM-IoT integration in construction safety?
- Are the research objectives clearly stated?
- Does the article provide insights relevant to the research questions?

The results of the data extraction process and data analysis are presented in Table 4 (see Appendix 1).

Step 7: Results presentation and interpretation
The integration of BIM and IoT offers significant advantages for OSH management (Figure 4). The bar chart visualises the number of references for each advantage of BIM-IoT integration in the OSH management. The findings highlight improved safety monitoring as the most cited advantage (17 references), reinforcing the role of real-time data collection and hazard detection in construction safety. Enhanced real-time decision-making and emergency response, referenced by 12 sources, further highlight the dynamic nature of BIM-IoT integration in preventing accidents and managing emergencies more efficiently. Additionally, enhanced hazard identification and risk assessment are strongly supported by 11 references, underscoring the proactive role of BIM-IoT in identifying and mitigating risks before incidents occur. Among design-phase benefits, hazard elimination during design received comparatively fewer references, indicating the need for broader adoption despite its recognised potential. Similarly, hazard visualisation (11 references) is frequently cited, underscoring its role in enhancing situational awareness and proactive safety planning. Additionally, improving workers' safety awareness and warning workers of workplace hazards were frequently noted, demonstrating the technology's role in fostering a safety-conscious culture. However, advantages such as enhanced near-miss reporting and compliance with safety regulations were less frequently referenced, suggesting areas for further exploration and improved implementation.

Overall, the results confirm that BIM-IoT integration enhances real-time monitoring, decision-making, and risk mitigation in construction safety. However, further research is needed to optimise its application in hazard prevention during the design phase and regulatory compliance.

4.2. Quantitative validation results
To validate the advantages identified through the systematic literature review and provide empirical evidence from the South African construction industry, a comprehensive survey was conducted among local construction professionals. This section presents the results of the quantitative analysis, including participant demographics, statistical validation and factor analysis of the advantages, and discussion of key findings.

4.2.1 Demographic Profile of Respondents
A total of 275 responses were collected, yielding 252 usable responses (91.6% response rate). The sample included a diverse range of company sizes, roles, and geographic locations within South Africa:

- 67% of respondents were in the 25-45 age range.
- Company size: 39% small (5-50 employees), 37% medium (51-200), 24% large (>200).
- Geographic distribution: 58% from Gauteng, 23% from the Western Cape, 10% from KwaZulu-Natal, and 9% from other provinces.

4.2.2 Technology familiarity & implementation
Respondents' familiarity and experience with BIM and IoT were assessed using 5-point Likert scales:

- BIM familiarity: Mean = 3.42 (SD = 1.18); 68% rated themselves moderate to high.

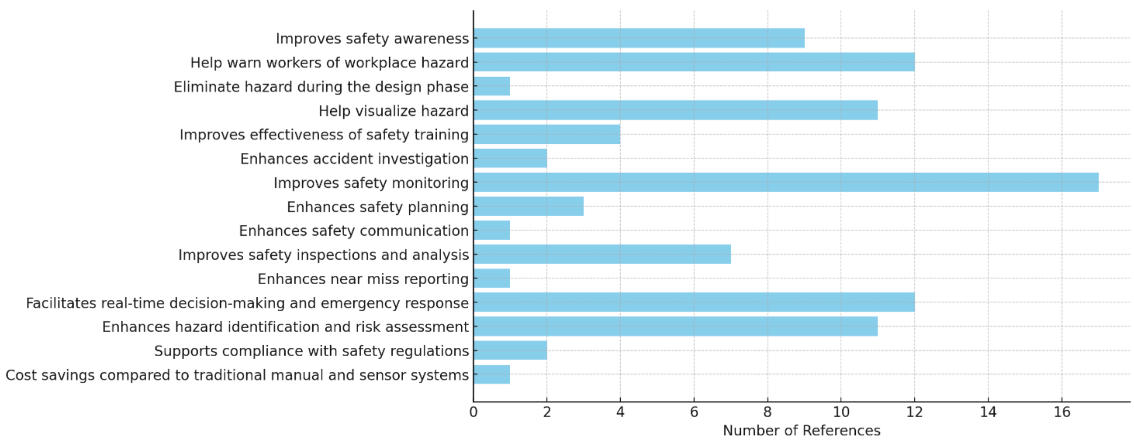

Figure 4: Advantages of BIM-IOT integration for OSH management

- IoT familiarity: Mean = 2.89 (SD = 1.24); 51% rated themselves moderate to high.
- 34.6% of companies reported implementing BIM in some projects; 23.7% reported using IoT devices for safety monitoring.

These findings indicate moderate BIM adoption while IoT implementation remains limited, suggesting significant potential for growth and integration.

4.2.3 Individual Advantage Rankings

Survey respondents evaluated each of the 15 advantages identified in the systematic literature review on a 5-point importance scale. Table 5 (see Appendix 1) presents the ranking based on mean scores.

4.2.4 Exploratory Factor Analysis (EFA) of BIM-IoT Advantages

EFA was performed on the 15 identified BIM-IoT advantages to explore the underlying factor structure. Results indicated high adequacy:

- Kaiser-Meyer-Olkin (KMO) = 0.892; Bartlett's Test of Sphericity: $\chi^2 = 3{,}247.8$, $p < 0.001$
- Five principal factors were identified with eigenvalues greater than 1.0, explaining 67.8% of total variance: Table 6 (see Appendix 1)
    1. Real-time Monitoring & Control
    2. Safety Planning & Design
    3. Training & Communication
    4. Investigation & Reporting
    5. Compliance & Economics

4.2.5 Confirmatory Factor Analysis (CFA)

CFA was performed to validate the measurement model using AMOS v29. The five-factor model demonstrated acceptable fit indices:

- $\chi^2/df = 2.47 < 3$(Threshold), CFI = 0.923 > 0.9 (Threshold), TLI = 0.908 > 0.9(Threshold), RMSEA = 0.076 < 0.08(Threshold), SRMR = 0.065 < 0.08(Threshold).
- All factor loadings were significant ($p < 0.001$) and exceeded the recommended threshold of 0.6, confirming the validity of the measurement model.

4.2.6 Reliability and Validity

All factors had Cronbach's α > 0.7, indicating good internal consistency (Table 7).

Table 7: Reliability and Validity Results

Factors	Cronbach's α	Mean	SD
Real-time Monitoring & Control	0.856	4.15	0.72
Safety Planning & Design	0.798	3.76	0.82
Training & Communication	0.821	3.92	0.72
Investigation & Reporting	0.776	3.72	0.85
Compliance & Economics	0.743	3.88	0.87

4.2.7 Key Findings Interpretation

The quantitative analysis validates the advantages identified through a systematic literature review while revealing important insights:

- Strong Literature-Practice Convergence: The top three ranked advantages in the survey ("Improve safety monitoring", "Real-time decision-making", and "Hazard identification") directly correspond to the most cited advantages in the SLR (17, 12, and 11 citations, respectively), demonstrating remarkable alignment between academic research and industry perceptions.
- Context-Specific Insights: Several advantages ranked higher in the survey than their literature citation frequency suggests, particularly "Supports compliance with safety regulations" (ranked 7th with only two citations) and "Cost savings" (ranked 11th with only 1 citation). This indicates that South African construction professionals place greater value on regulatory and economic benefits than the global literature suggests.
- Implementation Gap: "Eliminate hazard during design phase" ranked lowest (15th) despite being recognised in literature, suggesting implementation challenges in translating design-phase benefits into practice.
- Factor Dominance: "Real-time Monitoring & Control" emerged as the dominant factor, accounting for 18.7% of variance and containing the four highest-ranked individual advantages, confirming the central importance of dynamic safety management capabilities.
- The five-factor structure provides a validated framework for understanding BIM-IoT safety benefits, with strong statistical evidence (67.8% variance explained, excellent reliability, and good model fit) supporting the

theoretical categorisation of advantages into distinct but related dimensions.

5. Discussion

The integration of systematic literature review findings with quantitative validation provides comprehensive evidence for BIM-IoT advantages in construction safety management. This mixed-method approach strengthens the evidence base while revealing important patterns and contextual considerations.

The survey results demonstrate remarkable alignment between global research emphasis and South African professional perceptions, with the top-ranked advantages- "Improve safety monitoring" (4.28), "Real-time decision-making" (4.22), and "Hazard identification" (4.19). These findings confirm that the most cited benefits in international literature (17, 12, and 11 references, respectively) are equally valued by local construction professionals.

These validated advantages highlight BIM-IoT's capability to transform safety management from a reactive to a proactive approach, particularly through real-time hazard detection and emergency response systems (Riaz et al., 2014; Ding et al., 2022). The five-factor statistical structure- Real-time Monitoring & Control (18.7% variance), Safety Planning & Design, Training & Communication, Investigation & Reporting, and Compliance & Economics- provides a validated framework explaining 67.8% of total variance.

Context-specific insights reveal important divergences. "Supports compliance with safety regulations" ranks significantly higher locally (7th) than its limited literature presence (2 citations) suggests, reflecting South Africa's stringent regulatory environment and the critical importance of compliance in the local construction industry. Conversely, "eliminate hazard during design phase" received the lowest ranking (15th, mean 3.47), indicating implementation barriers despite theoretical recognition (Hu et al., 2024). This under-prioritisation likely reflects contractual fragmentation that limits the transfer of safety knowledge between design and construction teams, limited early involvement of safety professionals in design phases, and the absence of Design for Safety (DfS) mandates in local regulations. BIM-IoT systems could address this by functioning as early-stage risk identification tools during virtual construction simulation, with real-time IoT feedback validating design assumptions on actual sites. Regulatory adoption of DfS frameworks could further incentivise design-phase integration.

While BIM familiarity (mean = 3.42) was moderate, only 34.6% of companies reported implementing BIM, and despite lower IoT familiarity (mean = 2.89), just 23.7% have adopted IoT devices for safety monitoring. This implementation gap indicates that limited familiarity is not the only barrier; cost concerns, insufficient digital infrastructure, and low organisational readiness also hinder adoption. For BIM, phased training programmes targeting project managers and site engineers, combined with integration into existing project workflows, could help translate familiarity into actual use. For IoT, pilot projects demonstrating clear return on investment and low-cost sensor solutions are essential to reduce perceived risk and uncertainty. Policymakers and industry bodies should therefore prioritise subsidised training, technology demonstration projects, and capacity-building initiatives to accelerate BIM-IoT adoption in the South African construction sector. Overall, while BIM-IoT demonstrates strong capabilities in real-time monitoring, further advancement is needed in design-phase safety and regulatory compliance applications.

6. Conclusion and Further Research

This study successfully addresses the research gap in the advantages of BIM-IoT integration through a mixed-methods approach combining a systematic literature review with quantitative validation from 252 South African construction professionals. The research provides both theoretical understanding and practical evidence for developing country contexts.

The systematic literature review identified fifteen advantages of BIM-IoT integration, with "improved safety monitoring" as the most cited benefit (17 references), followed by "enhanced real-time decision-making and emergency response" (12 references) and "enhanced hazard identification and risk assessment" (11 references). The quantitative validation strongly confirmed these findings, with the same advantages receiving the highest importance ratings from industry professionals (means 4.28, 4.22, and 4.19, respectively).

The statistical analysis revealed five underlying dimensions of advantages explaining 67.8% of total variance, providing a validated framework for understanding integrated technology advantages. All factors demonstrated excellent reliability (Cronbach's $\alpha > 0.7$), and the measurement model showed good fit indices, confirming the validity of the theoretical framework. The convergence between literature citations and professional ratings validates the global applicability of core BIM-IoT safety advantages.

However, despite these advantages, certain areas, such as hazard elimination during the design phase and regulatory compliance support, reveal implementation challenges. The limited emphasis on design-phase applications in literature, combined with the lowest survey ranking (15th, mean 3.47), suggests that while BIM-IoT holds promise for improving safety from the early design stage, practical adoption and implementation barriers persist. Conversely, regulatory compliance received a higher local priority than in the global literature, reflecting context-specific needs in developing economies.

The technology implementation gap, where IoT familiarity (2.89) significantly lags behind BIM familiarity (3.42), indicates substantial opportunities for growth and innovation in the South African construction sector. Only 23.7% of surveyed companies have implemented IoT for safety monitoring, suggesting significant potential for competitive advantage through early adoption.

6.1. Practical Implications and Prioritisation Framework

The five-factor structure identified in this study- Real-time Monitoring & Control, Safety Planning & Design, Training & Communication, Investigation & Reporting, and Compliance & Economics- provides a validated prioritisation framework that organisations can use to stage BIM-IoT investments strategically. Rather than implementing all advantages simultaneously, companies can adopt a phased approach: (1) **Phase 1 (Foundation):** prioritise Real-time Monitoring & Control and Safety Planning & Design, which account for the largest variance (18.7% and 14.1%) and address immediate safety concerns; (2) **Phase 2 (Enablement):** introduce Training & Communication systems to build workforce capability alongside technology deployment; (3) **Phase 3 (Optimisation):** develop Investigation & Reporting protocols to capture lessons learned and continuously improve safety; (4) **Phase 4 (Strategic):** integrate Compliance & Economics considerations to demonstrate ROI and secure ongoing stakeholder support. This staged approach allows organisations to distribute implementation costs, build internal expertise progressively, and accumulate evidence of safety improvements- particularly relevant for companies in developing country contexts with limited initial capital investment capacity. The framework thus serves not only as a theoretical model but as an actionable decision-support tool for construction industry practitioners.

6.2. Study Limitations

This study has several limitations that should be acknowledged. First, the survey sample was geographically concentrated in urban provinces, which may not fully represent rural or remote construction practices in South Africa. Second, the study relied on self-reported perceptions of BIM-IoT advantages rather than objective performance measures or longitudinal tracking of actual safety improvements. Third, while the SLR focused on three major indexed databases (ScienceDirect, Scopus, Web of Science) to ensure quality and consistency, this approach may have excluded relevant grey literature, regional practitioner reports, and industry publications from developing countries that were not indexed.

6.3. Recommendations for Future Research

Future research should focus on enhancing BIM-IoT integration for design-phase hazard prevention, optimising predictive safety analytics, and standardising safety compliance frameworks. Specific research priorities include: longitudinal studies tracking actual safety performance improvements following BIM-IoT implementation, investigation of barriers preventing design-phase integration, development of automated regulatory compliance tools, exploration of advanced applications including AI-driven safety monitoring and predictive hazard identification, and comparative analyses across demographic subgroups to identify whether implementation strategies should be tailored differently for small vs. large companies or novice vs. experienced BIM/IoT users.

Addressing these gaps requires further research and industry-driven innovations to optimise BIM-IoT frameworks for holistic safety management. The evidence base established in this study provides a foundation for evidence-based investment decisions while highlighting the potential for BIM-IoT integration to transform construction safety management from a reactive to a proactive paradigm in developing country contexts.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

Alomari, K., Gambatese, J., & Anderson, J. (2017). Opportunities for using building information modeling to improve worker safety performance. *Safety*, *3*(1), 7.

Amiri, M., Saghatforoush, E., & Laryea, S. (2024). Using dynamic BIM to improve construction safety culture.

Augustin, A., Yi, J., Clausen, T., & Townsley, W. M. (2016). A study of LoRa: Long range & low power networks for the internet of things. *Sensors*, *16*(9), 1466.

Azhar, S. (2017). Role of visualisation technologies in safety planning and management at construction jobsites. *Procedia engineering*, *171*, 215-226.

Chatzimichailidou, M., & Ma, Y. (2022). Using BIM in the safety risk management of modular construction. *Safety science*, *154*, 105852.

Chen, H., Hou, L., Zhang, G. K., & Moon, S. (2021). Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. *Automation in Construction*, *125*, 103631.

Cheng, T., & Teizer, J. (2013). Real-time resource location data collection and visualisation technology for construction safety and activity monitoring applications. *Automation in construction*, *34*, 3-15.

Cheung, W. F., Lin, T. H., & Lin, Y. C. (2018). A real-time construction safety monitoring system for hazardous gas integrating wireless sensor network and building information modeling technologies. *Sensors*, *18*(2), 436.

Construction Industry Development Board (CIDB). (2022). Annual Report 2021/2022. Construction Industry Development Board, South Africa.

Cortés-Pérez, J. P., Cortés-Pérez, A., & Prieto-Muriel, P. (2020). BIM-integrated management of occupational hazards in building construction and maintenance. *Automation in Construction*, *113*, 103115.

Dave, B., Buda, A., Nurminen, A., & Främling, K. (2018). A framework for integrating BIM and IoT through open standards. *Automation in construction*, *95*, 35-45.

Department of Employment and Labour. (2022). Occupational Health and Safety Statistics 2022. Republic of South Africa: Department of Employment and Labour.

Ding, L. Y., Zhou, C., Deng, Q. X., Luo, H. B., Ye, X. W., Ni, Y. Q., & Guo, P. (2013). Real-time safety early warning system for cross passage construction in Yangtze Riverbed Metro Tunnel based on the internet of things. *Automation in construction*, *36*, 25-37.

Ding, L., Jiang, W., & Zhou, C. (2022). IoT sensor-based BIM system for smart safety barriers of hazardous energy in petrochemical construction. *Frontiers of Engineering Management*, *9*(1), 1-15.

Ding, L., Zhou, Y., & Akinci, B. (2014). Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD. *Automation in construction*, *46*, 82-93.

Fan, W., Zhou, J., Zhou, J., Liu, D., Shen, W., & Gao, J. (2021). Safety management system prototype/framework of deep foundation pit based on BIM and IoT. *Advances in Civil Engineering*, *2021*(1), 5539796.

Ganah, A., & John, G. A. (2015). Integrating building information modeling and health and safety for on-site construction. *Safety and health at work*, *6*(1), 39-45.

Getuli, V., Giusti, T., Capone, P., Sorbi, T., & Bruttini, A. (2018). A project framework to introduce virtual reality in construction health and safety. *IN_BO. Ricerche e progetti per il territorio, la città e l'architettura*, *9*(13), 166-175.

Glasziou, P., Irwig, L., Bain, C., & Colditz, G. (2001). *Systematic reviews in health care: a practical guide*. Cambridge University Press.

Han, S., Peña-Mora, F., Golparvar-Fard, M., & Roh, S. (2009). Application of a visualisation technique for safety management. In *Computing in Civil Engineering (2009)* (pp. 543-551).

Heidary Dahooie, J., Vanaki, A. S., Firoozfar, H. R., Zavadskas, E. K., & Čereška, A. (2020). An extension of the failure mode and effect analysis with hesitant fuzzy sets to assess the occupational hazards in the construction industry. *International Journal of Environmental Research and Public Health*, *17*(4), 1442.

Henderson, L. K., Craig, J. C., Willis, N. S., Tovey, D., & Webster, A. C. (2010). How to write a Cochrane systematic review. *Nephrology*, *15*(6), 617-624.

Hossain, M. M., Ahmed, S., Anam, S. A., Baxramovna, I. A., Meem, T. I., Sobuz, M. H. R., & Haq, I. (2023). BIM-based smart safety monitoring system using a mobile app: a case study in an ongoing construction site. *Construction Innovation*.

Hu, X., Olgun, G., & Assaad, R. H. (2024). An intelligent BIM-enabled digital twin framework for real-time structural health monitoring using wireless IoT sensing, digital signal processing, and structural analysis. *Expert Systems with Applications*, *252*, 124204.

Jiang, H., & Jiang, A. (2024). An integrated system for tunnel construction safety control based on BIM–IoT–PSO. *Journal of Civil Structural Health Monitoring*, *14*(2), 269-284.

Jiang, Z. H., Huang, F., Wang, D. X., Hu, B., & Dou, J. J. (2013). The design and implementation of a construction site safety supervisory system based on the Internet of Things. *Applied Mechanics and Materials*, *241*, 3190-3194.

Jin, R., Zou, P. X., Piroozfar, P., Wood, H., Yang, Y., Yan, L., & Han, Y. (2019). A science mapping approach-based review of construction safety research. *Safety science*, *113*, 285-297.

Kanan, R., Elhassan, O., & Bensalem, R. (2018). An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies. *Automation in Construction*, *88*, 73-86.

Kiani, A., Salman, A., & Riaz, Z. (2014). Real-time environmental monitoring, visualisation, and notification system for construction H&S management. *Journal of Information Technology in Construction*, *19*, 72-91.

Kim, K., Cho, Y., & Zhang, S. (2016). Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM. *Automation in Construction*, *70*, 128-142.

Kim, T., & Chi, S. (2019). Accident case retrieval and analyses: Using natural language processing in the construction industry. *Journal of Construction Engineering and Management*, *145*(3), 04019004.

Li, H., Lu, M., Chan, G., & Skitmore, M. (2015). Proactive training system for safe and efficient precast installation. *Automation in Construction*, *49*, 163-174.

Liang, Y., & Liu, Q. (2022). Early warning and real-time control of construction safety risk of underground engineering based on building information modelling and the Internet of Things. *Neural Computing and Applications*, 1-10.

Luo, F., Li, R. Y. M., Crabbe, M. J. C., & Pu, R. (2022). Economic development and construction safety research: A bibliometrics approach. *Safety science*, *145*, 105519.

Miles, J., & Whitehouse, N. (2013). Offsite housing review. *Department of Business, Innovation & Skills and the Construction Industry Council, London*.

Mohammed, B. H., Safie, N., Sallehuddin, H., & Hussain, A. H. B. (2020). Building information modelling (BIM) and the internet-of-things (IoT): a systematic mapping study. *IEEE Access*, *8*, 155171-155183.

Mohd-Nor, M. F. I., Tahir, M. M., Usman, I. M. S., & Ismail, A. H. (2019). The usage of building information modelling (BIM) in Malaysia's architecture industry. *Journal of Design+ Built*, *12*(1).

Nadhim, E. A., Hon, C., Xia, B., Stewart, I., & Fang, D. (2016). Falls from height in the construction industry: A critical review of the scientific literature. *International journal of environmental research and public health*, *13*(7), 638.

Pang, B., Shi, J., Jiang, L., & Pan, Z. (2024). A Semantic Approach to Dynamic Path Planning for Fire Evacuation through BIM and IoT Data Integration. *Advances in Civil Engineering*, *2024*(1), 8839865.

Park, M. W., & Brilakis, I. (2012). Construction worker detection in video frames for initialising vision trackers. *Automation in Construction*, *28*, 15-25.

Parn, E. A., Edwards, D., Riaz, Z., Mehmood, F., & Lai, J. (2019). Engineering-out hazards: digitising the management working safety in confined spaces. *Facilities*, *37*(3/4), 196-215.

Qian, H. (2021, July). Design of a tunnel automatic monitoring system based on BIM and IoT. In *Journal of Physics: Conference Series* (Vol. 1982, No. 1, p. 012073). IOP Publishing.

Ray, S. J., & Teizer, J. (2012). Real-time construction worker posture analysis for ergonomics training. *Advanced Engineering Informatics*, *26*(2), 439-455.

Riaz, Z., Arslan, M., Kiani, A. K., & Azhar, S. (2014). CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined spaces. *Automation in construction*, *45*, 96-106.

Riaz, Z., Parn, E. A., Edwards, D. J., Arslan, M., Shen, C., & Pena-Mora, F. (2017). BIM and sensor-based data management system for construction safety monitoring. *Journal of Engineering, Design and Technology*, *15*(6), 738-753.

Sakr, M., & Sadhu, A. (2023). Visualisation of structural health monitoring information using Internet-of-Things integrated with building information modeling. *Journal of Infrastructure Intelligence and Resilience*, *2*(3), 100053.

Saldaña, J. (2021). The coding manual for qualitative researchers.

Scianna, A., Gaglio, G. F., & La Guardia, M. (2022). Structure monitoring with BIM and IoT: The case study of a bridge beam model. *ISPRS International Journal of Geo-Information*, *11*(3), 173.

Seo, J., Han, S., Lee, S., & Armstrong, T. J. (2013). Motion data-driven unsafe pose identification through biomechanical analysis. In *Computing in Civil Engineering (2013)* (pp. 693-700).

Tabatabaee, S., Mohandes, S. R., Ahmed, R. R., Mahdiyar, A., Arashpour, M., Zayed, T., & Ismail, S. (2022). Investigating the barriers to applying the Internet of Things-based technologies to construction site safety management. *International journal of environmental research and public health*, *19*(2), 868.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in construction*, *101*, 127-139.

Teizer, J., Cheng, T., & Fang, Y. (2013). Location tracking and data visualisation technology to advance construction ironworkers' education and training in safety and productivity. *Automation in construction*, *35*, 53-68.

Wang, J., Lim, M. K., Wang, C., & Tseng, M. L. (2021). The evolution of the Internet of Things (IoT) over the past 20 years. *Computers & Industrial Engineering*, *155*, 107174.

Wright, R. W., Brand, R. A., Dunn, W., & Spindler, K. P. (2007). How to write a systematic review. *Clinical Orthopaedics and Related Research®*, *455*, 23-29.

Xiaer, X., Dib, H., Yuan, J., Tang, Y., & Li, Q. (2016, September). Design for safety (DFS) and building information modeling (BIM): A review. In *International Conference on Construction and Real Estate Management 2016* (pp. 69-80). Reston, VA: American Society of Civil Engineers.

Yang, X., Yu, Y., Shirowzhan, S., & Li, H. (2020). Automated PPE-Tool pair check system for construction safety using smart IoT. *Journal of Building Engineering*, *32*, 101721.

Ying, D., Cheong, C. B., & Zou, Y. (2021, February). Engineering Safety Early Warning Platform Based on BIM and Internet of Things. In *Journal of Physics: Conference Series* (Vol. 1744, No. 2, p. 022002). IOP Publishing.

Yuan, X., & Anumba, C. J. (2020). Cyber-physical systems for temporary structures monitoring. *Cyber-physical systems in the built environment*, 107-138.

Zhang, M., Cao, T., & Zhao, X. (2017). Applying sensor-based technology to improve construction safety management. *Sensors*, *17*(8), 1841.

Zhang, Y., & Bai, L. (2015). Rapid structural condition assessment using radio frequency identification (RFID) based wireless strain sensor. *Automation in Construction*, *54*, 1-11.

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. *Safety science*, *72*, 337-350.

Zou, Y., Kiviniemi, A., & Jones, S. W. (2017). A review of risk management through BIM and BIM-related technologies. *Safety science*, *97*, 88-98.

Appendix 1

Table 4: Advantages of using BIM-IOT integration for OSH Management

N	Advantages	References
1	Improve safety awareness	Fan et al (2021), Ding et al (2013), Cheng and Teizer (2013), Kiani et al (2014), Li et al (2015), Ding et al (2022), Parn et al (2019), Chen et al (2021), Riaz et al (2014)
2	Help warn workers of workplace hazard	Fan et al (2021), Ding et al (2013), Kiani et al (2014), Li et al (2015), Parn et al (2019), Liang and Liu (2022), Chen et al (2021), Qian (2021), Hossain et al (2023), Yuan and Anumba (2020), Cheung et al (2018), Riaz et al (2014)
3	Eliminate hazard during the design phase	Hu et al (2024)
4	Help visualize hazard	Sakr and Sadhu (2023), Scianna et al (2022), Fan et al (2021), Ding et al (2013), Cheng and Teizer (2013), Kiani et al (2014), Zhang and Bai (2015), Li et al (2015), Parn et al (2019), Hossain et al (2023), Hu et al (2024)
5	Improves effectiveness of safety training	Fan et al (2021), Cheng and Teizer (2013), Li et al (2015), Teizer et al (2013)
6	Enhancing accident investigation	Scianna et al (2022), Li et al (2015)
7	Improve safety monitoring	Sakr and Sadhu (2023), Scianna et al (2022), Cheng and Teizer (2013), Fan et al (2021), Kiani et al (2014), Zhang and Bai (2015), Li et al (2015), Ding et al (2022), Liang and Liu (2022), Chen et al (2021), Qian (2021), Hossain et al (2023), Riaz et al (2017), Yuan and Anumba (2020), Hu et al (2024), Jiang and Jiang (2024), Cheung et al (2018)
8	Enhancing safety planning	Scianna et al (2022), Fan et al (2021), Pang et al (2024)
9	Enhancing safety communication	Yuan and Anumba (2020)
10	Improve safety inspections and analysis	Sakr and Sadhu (2023), Scianna et al (2022), Fan et al (2021), Li et al (2015), Ying et al (2021), Yuan and Anumba (2020), Riaz et al (2014)
11	Enhancing near miss reporting	Li et al (2015)
12	Facilitating real-time decision-making and emergency response	Sakr and Sadhu (2023), Ding et al (2013), Cheng and Teizer (2013), Zhang and Bai (2015), Li et al (2015), Parn et al (2019), Chen et al (2021), Qian (2021), Yuan and Anumba (2020), Pang et al (2024), Cheung et al (2018), Riaz et al (2014)
13	Enhancing hazard identification and risk assessment	Scianna et al (2022), Kiani et al (2014), Zhang and Bai (2015), Li et al (2015), Qian (2021), Riaz et al (2017), Yuan and Anumba (2020), Hu et al (2024), Jiang and Jiang (2024), Pang et al (2024), Cheung et al (2018)
14	Supports compliance with safety regulations	Ding et al (2022), Liang and Liu (2022)
15	Cost savings compared to traditional manual and sensor systems	Hossain et al (2023)

Table 5: Ranking of BIM-IoT Safety Advantages (Based on Survey Results)

Rank	Advantage	Mean Score	SD	SLR Citation
1	Improve safety monitoring	4.28	0.68	17
2	Facilitating real-time decision-making and emergency response	4.22	0.71	12
3	Enhancing hazard identification and risk assessment	4.19	0.73	11
4	Help warn workers of workplace hazards	4.12	0.76	12
5	Improve safety awareness	4.08	0.78	9
6	Help visualise hazard	3.98	0.82	11
7	Supports compliance with safety regulations	3.94	0.85	2
8	Improves the effectiveness of safety training	3.91	0.79	4
9	Improve safety inspections and analysis	3.87	0.83	7
10	Enhancing safety planning	3.84	0.86	3
11	Cost savings compared to traditional systems	3.81	0.88	1
12	Enhancing safety communication	3.76	0.84	1
13	Enhancing accident investigation	3.68	0.89	2
14	Enhancing near miss reporting	3.61	0.93	1
15	Eliminate hazards during the design phase	3.47	0.97	1

Table 6: Factor Analysis Results - Five-Factor Solution

Factors	Advantages	Factor Loading	Eigenvalue	Variance Explained
Factor 1: Real-time Monitoring & Control			**4.23**	**18.7%**
	Enhances safety monitoring	0.834		
	Facilitating real-time decision-making and emergency response	0.789		
	Enhancing hazard identification and risk assessment	0.756		
	Help warn workers of workplace hazards	0.678		
Factor 2: Safety Planning & Design			**3.18**	**14.1%**
	Enhancing safety planning	0.812		
	Eliminate hazards during the design phase	0.745		
	Help visualise hazard	0.698		
Factor 3: Training & Communication			**2.89**	**12.8%**
	Improve safety awareness	0.823		
	Improves the effectiveness of safety training	0.756		
	Enhancing safety communication	0.689		
Factor 4: Investigation & Reporting			**2.67**	**11.8%**
	Improve safety inspections and analysis	0.798		
	Enhancing accident investigation	0.734		
	Enhancing near miss reporting	0.687		
Factor 5: Compliance & Economics			**2.34**	**10.4%**
	Supports compliance with safety regulations	0.812		
	Cost savings compared to the traditional system	0.745		

JCBM (2025) 8(S1) 140-154

University of Cape Town

Journal of Construction Business and Management

http://journals.uct.ac.za/index.php/jcbm

Evaluation of Sustainable Building Technologies Adoption in Housing Construction Across Socio-Economic Contexts in Cape Town, South Africa

Kabemba S. Ngoy[1], Esona Daweti[2], Relebohile Molise[3], Darmarajan Chinasamy[4] and Abimbola Windapo[5]

[1-5]Department of Construction Economics and Management, Faculty of Engineering and the Built Environment, University of Cape Town, South Africa

Received 15 October 2025; received in revised form 17 October 2025, 16 December 2025; accepted 28 December 2025
https://doi.org/10.15641/jcbm.8.S1.1948

Abstract

This research aims to evaluate adoption patterns and key factors influencing the adoption of innovative sustainable building materials in housing across socio-economic contexts in Cape Town, South Africa, to identify targeted interventions that promote equitable access. A mixed-methods approach was used to collect data through semi-structured interviews and survey questionnaires, distributed randomly to Cape Town residents and purposively to professionals working on housing construction projects. The collected data were analysed using descriptive, thematic, and inferential statistical techniques. The study found that most respondents from both classes were aware of sustainable building technologies and materials and perceived that environmentally friendly building materials reduce the environmental impact of construction. The majority of low-income respondents lack access to government assistance and other financial resources compared to middle- and high-income respondents. Both groups utilise recycled materials more often than not. No significant differences were found in the main variables influencing respondents' choices regarding the use of sustainable building materials across the middle- and lower-class groups. In South Africa, the adoption of sustainable building practices is impeded by socio-economic constraints, technological limitations, economic barriers, and insufficient awareness. This study advances knowledge of how economic circumstances affect, at different levels, the use of sustainable building materials and technology in housing construction. The study recommends that governments and financial institutions launch initiatives, such as training and financial incentives, to equip stakeholders with the information they need to increase the likelihood of adopting sustainable practices.

Keywords: Environmental impact, Housing, Income level, Sustainable building technologies, South Africa.

1. Introduction

The construction sector is a major contributor to global environmental degradation, driving urgent calls for sustainable practices, particularly in rapidly urbanising regions like South Africa. This study offers a thorough contextual overview of the topic, highlighting the major variables influencing the uptake of sustainable building materials and technologies, illuminating inequalities, and suggesting tactics to foster more equitable access to sustainable housing options.

The adoption patterns of sustainable building materials and technologies in housing construction vary significantly across different socio-economic contexts, influenced by a multitude of factors (Eze *et al.*, 2021). Economic and socio-cultural contexts are particularly pivotal in shaping the acceptance of sustainable housing technologies (Okitasari *et al.*, 2022). These socio-economic contexts include a wide range of social and economic conditions that influence housing construction, including cost considerations, access to information and education, regulatory environment, cultural factors, infrastructure and resources, and climate change impacts.

Several other variables significantly influence adoption trends, in addition to socio-economic factors. According to Khudzari *et al.* (2021), these variables include perceptions of risk and uncertainty around new technologies, the accessibility and availability of

[1] Corresponding Author
Email address: kabembasteve7@gmail.com

sustainable building materials and technologies, technical elements such as building systems and construction techniques, customer preferences, and market demand. Understanding how these factors interact is crucial to formulating strategies that effectively promote the broad adoption of sustainable building practices in the industry. By addressing the imbalance between the knowledge of sustainable materials and technologies and their affordability, this study seeks to provide insights into ways to encourage more equitable and sustainable practices in the construction sector. Sustainable building materials are carefully selected resources that minimise environmental impact while simultaneously promoting social and economic well-being (Okogwu *et al.,* 2023). Moghayedi *et al.* (2022) and Afanasyeva *et al.* (2020) emphasised the substantial influence of enablers and legal standards on the adoption of sustainable practices in housing developments. This influence, in turn, has implications for socio-economic accessibility, shaping the extent to which sustainable housing solutions are accessible to different segments of society. According to Turcotte and Geiser (2015), sustainable housing development has three principles that serve as a definitional tool, meaning it must address environmental, economic, and social factors to be deemed truly sustainable (Shama and Motlak, 2019). This suggests the need for integrated measures that not only reduce environmental effects but also improve cost-effectiveness, equity, and social welfare.

Housing construction is a fundamental aspect of societal development, yet conventional practices often result in environmental degradation and social inequities (Kennedy *et al.*, 2009). Historical analyses show that resource-intensive building practices have repeatedly caused environmental damage and economic inequality (Kennedy et al., 2009). According to Wang et al. (2018) and AlSanad (2015), buildings and the construction sector utilise substantial resources worldwide and have a significant impact on the environment, leading to high energy use and greenhouse gas emissions. According to Kennedy et al. (2009), the housing sector accounts for up to 40% of overall energy consumption. It generates roughly one-third of greenhouse gas emissions across several stages, including the extraction, processing, manufacturing, transportation, construction, and building operation.

Sustainable construction is a strategy to achieve sustainable development and address environmental challenges posed by population growth and increased consumption (Alabi and Fapohunda, 2021). Recent decades have witnessed a growing emphasis on sustainability in the built environment, catalysed by concerns over climate change and resource depletion (Kennedy *et al.*, 2009). Therefore, governments and individuals must find innovative alternatives for sustainable development, and as a result, most countries are working to implement sustainable construction practices to reduce environmental impacts (Alabi and Fapohunda, 2021). Wang *et al.* (2018) noted that Sustainable development, particularly through green building practices and innovative building materials, has emerged as a solution to these challenges, promoting eco-friendly materials and resource-efficient construction. Green Building Technologies and Sustainable Building Materials also play a key role in improving energy efficiency and environmental performance. Building owners must effectively integrate these practices into architectural design to transform traditional buildings into sustainable structures and advance the sustainable building industry (Wang *et al.*, 2018). However, promoting these sustainable practices faces obstacles, especially in developing countries where traditional building practices dominate (AlSanad, 2015).

The adoption of innovative sustainable building materials and technologies in housing construction across socio-economic contexts presents a significant challenge, marked by disparities in adoption rates and accessibility (Khudzari *et al.*, 2021). Despite notable advancements in sustainable building practices, various factors contribute to uneven adoption patterns, hindering widespread implementation.

In many communities, the adoption of sustainable building practices is impeded by socio-economic constraints, technological limitations, economic barriers, and insufficient awareness (Marsh *et al.*, 2020). While some regions readily embrace sustainable alternatives, others remain reliant on traditional, resource-intensive construction methods. This imbalance is particularly evident in South Africa and other regions, where disparities exist in both the knowledge and affordability of sustainable building materials and technologies (Marsh *et al.*, 2020). For instance, developers in areas like Malaysia face obstacles in meeting the growing demand for housing while upholding social and ecological responsibility (Abidin, 2010). Developing countries like Nigeria face barriers in adopting sustainable construction practices (Alabi and Fapohunda, 2021). Despite significant progress in researching the uptake of green buildings in developing countries, recent studies reveal a continued gap in understanding the theoretical and contextual factors influencing the adoption of innovative building materials and technologies in Africa (Mushi *et al.*, 2023).

However, despite the growing body of literature on sustainable construction, there remains a significant gap in understanding how socio-economic factors specifically influence the adoption of sustainable building technologies in Cape Town. Previous studies have often focused on either high-income contexts or broad national trends, lacking a nuanced comparison across income groups within a single urban setting. This study addresses this gap by examining how socio-economic disparities in Cape Town, a city marked by profound inequality, affect access to and adoption of sustainable building materials and technologies, and by identifying the main variables influencing adoption rates, the key implementation obstacles, and the targeted interventions needed to advance sustainable practices. By doing so, the study seeks to generate context-specific insights currently missing from the literature and to provide evidence that can help policymakers and industry practitioners promote the broader adoption of sustainable construction methods, while simultaneously supporting socio-economic development and environmental sustainability by bridging the knowledge and affordability gaps.

2. Literature Review

The adverse environmental impacts of the construction industry cannot be overlooked, as it plays a significant role in the country's economic development. Therefore, it is emphasised that sustainability practices must be integrated within construction operations to ensure that the economic development brought by the construction sector is environmentally responsible (Khalid Mehmood Sadar and Ishak, 2024). Sustainable construction, as defined by Yılmaz and Bakış (2015), involves applying sustainable development principles throughout a building's life cycle, from planning and construction to material sourcing, usage, waste management, and demolition. Green building, according to the United States Environmental Protection Agency USEPA, 2016), focuses on environmentally responsible and resource-efficient practices throughout a building's lifespan, offering an alternative to traditional construction methods to reduce negative environmental impacts and combat climate change. The adoption of Green Building Technologies (GBTs) is essential for achieving green building goals (Chan *et al.*, 2018).

A more comprehensive approach to sustainable development is made possible by the adoption of Green Building Technologies (GBTs), which are defined by the World Green Building Council (WGBC) as structures that offer comfort, cost savings, and a reduced environmental impact (Gohari et al., 2024; Ahmad et al., 2019). Since buildings are primarily responsible for energy use and carbon emissions, the construction sector has a significant influence on sustainable development and environmental preservation worldwide. Health problems are caused by pollution and harmful gas emissions from construction activities (Cao et al., 2022).

Huang (2015) highlighted that the construction industry is the most significant contributor to global carbon dioxide emissions, driven by the materials and methods used in traditional building practices. This sector is a major factor in environmental degradation, posing risks to future generations. Estimates suggest that construction activities contribute to 25% of global deforestation, with additional emissions from industrialised nations accounting for 10%. Emissions include 39% carbon dioxide, 49% sulfur dioxide, and 25% nitrous oxide, with 40% attributed to raw material extraction (Eze *et al.*, 2023). This is primarily due to conventional building methods and materials. Its impact on environmental degradation underscores the need for a shift towards a circular economy approach in construction to mitigate adverse effects (Saha *et al.*, 2021). Addressing environmental challenges and climate change in the construction sector is crucial, as buildings account for a significant share of global energy use and greenhouse gas emissions.

2.1. Importance of Sustainable Construction

According to Yılmaz and Bakış (2015), sustainable construction is important because it integrates sustainable development concepts throughout the building life cycle. Sustainable construction techniques are critical throughout the whole construction process, from raw material sourcing to demolition and waste management. By incorporating these ideas, sustainable construction guarantees that present demands are addressed while preserving future generations' ability to meet their own needs. It adheres to the three pillars of sustainability; environmental, social, and economic by minimising environmental consequences, promoting social fairness, and maintaining economic viability. This strategy is critical for developing resilient, resource-efficient buildings that will have a positive impact on the future.

2.2. Key Principles of Sustainable Construction

The goal of sustainable construction is to reduce the environmental impact of constructing and maintaining structures while simultaneously creating cosy, healthy spaces. Purvis et al. (2019) examined records from the International Union for Conservation of Nature (IUCN) to determine the origins of the three main pillars of sustainability: social, economic, and environmental. The study found that since the beginning, the three pillars have been closely related to the idea of sustainable development. They illustrate the roots of the well-known circles' diagram and the framework that encourages the attainment of the goals of the three systems.

2.2.1. Economic Sustainability

Economic sustainability is the consistent flow of public and private investments, along with the efficient utilisation and management of resources (Yılmaz and Bakış, 2015). They emphasise evaluating economic efficiency on social criteria rather than organisational profitability alone. The study highlights the potential to enhance economic sustainability in the construction sector by improving industry structure and performance. Additionally, the labour-intensive nature of the construction industry can improve the quality of life by creating job opportunities for individuals with lower incomes.

2.2.2. Social Sustainability

Social Sustainability, as defined by Yılmaz and Bakış (2015), emphasises fundamental human rights and freedoms. It involves ensuring access to essential needs like employment, housing, healthcare, education, and cultural opportunities for all individuals over an extended period. In addition, Eizenberg and Jabareen (2017) introduced a conceptual framework for social sustainability aimed at improving individuals' well-being. The framework consists of four interconnected concepts: equity, safety, eco-prosumption, and sustainable urban forms. It highlighted the need for a theoretical foundation in selecting social sustainability indicators, as current practices often lack a clear definition and are influenced by practical considerations and political agendas.

2.2.3. Environmental Sustainability

Environmental sustainability involves leaving the world in a better state for future generations by preserving ecological balance and natural systems (Yılmaz and Bakış, 2015). This responsibility includes decreasing energy and resource consumption, minimising construction waste and energy usage, reducing external pollution and environmental harm, and minimising internal pollution and health risks. Gohari *et al.*, (2024) elaborate on environmental responsibility, highlighting the commitment to minimising the environmental footprint of construction activities by reducing energy consumption, waste generation, and greenhouse gas emissions. By prioritising these strategies, the construction industry can contribute to broader environmental goals such as biodiversity conservation and sustainable resource management.

In response to urgent environmental issues including resource depletion and climate change, the conventional emphasis on cost, time, and quality in construction management is being expanded to incorporate environmental responsibility (Dosumu and Aigbavboa, 2018). In line with international initiatives to combat climate change and resource depletion, incorporating green materials and sustainable practices into construction management can help reduce adverse environmental effects and advance long-term sustainability in built environments. Therefore, promoting sustainable development goals and guaranteeing the prudent use of natural resources depend on construction management placing a high priority on environmental responsibility.

2.3. Sustainable Building Materials and Technologies

The construction industry is adopting sustainable building materials and technology to reduce environmental impact and improve long-term viability (Javaid *et al.*, 2022). Sustainable methods currently transforming South Africa include using innovative materials such as bamboo, precast concrete, cross-laminated timber, and straw bales, as well as incorporating technologies such as BIM and 3-D printing.

2.4. Innovative Materials

In South Africa, the construction industry is changing as more people become aware of environmental issues and look for greener ways to build (Windapo, 2014). With problems like limited resources and climate change, the focus has shifted to materials that can help both the environment and the economy (Korhonen *et al.*, 2018). These materials are influencing how buildings are designed and built, offering a future where both the planet and people benefit (Raji *et al.*, 2015). Bamboo is strong and flexible; precast concrete is durable and efficient; cross-laminated timber is strong and stable; and straw bales offer excellent insulation. Each one is setting new standards for eco-friendly construction, offering access to buildings that are better for the environment, affordable, and fit the growing demand for sustainable living (Korhonen *et al.*, 2018). Thus, shaping a more sustainable and innovative construction.

2.5. Factors Influencing the Adoption of Sustainable Building Materials and Technologies

2.5.1. Socio-economic Classification in Housing Studies

Socio-economic context

Socio-economic context refers to the combination of social and economic factors that affect a range of outcomes, both positively and negatively, including health, well-being, and living standards (Baker, 2014). Common ways to measure socio-economic status include examining an individual's level of education, income, and occupation. Weilenmann *et al.* (2017) emphasise the importance of investigating economic, demographic, and social issues to better understand the situation. According to Khan *et al.* (2014), in construction, these factors are directly linked to the stages of a country's economic growth and impact industry practices. Furthermore, (Bornstein and Bradley, 2014) show that socio-economic factors may affect people's willingness to employ sustainable construction materials and technology, resulting in different adoption patterns.

Income Levels

Albert *et al.*, (2018) used the monthly income of a family of five to distinguish between different socio-economic groups. The study found that income levels can be defined according to multiples of the poverty line, with per-capita income used to differentiate between different socio-economic categories. Households earning less than the official poverty threshold are deemed poor, whereas those earning between the poverty line and twice that amount are classified as low-income but not impoverished. The classification continues with the lower-middle-income group, earning between two and four times the poverty threshold, followed by the middle-middle-income group, earning four to seven times the poverty threshold. Upper-middle- income households earn seven to twelve times the poverty limit. Those earning between twelve and twenty times the poverty line are considered upper-income but not rich, while the rich earn at least twenty times the poverty line. This concept provides a detailed breakdown of income clusters across various socio-economic groups.

Study by Krausmann *et al.*, (2017) states that in the second half of the twentieth century growth in material use was partly driven by rising income and consumption in the industrial world. This means that the largest share of materials has been consumed in high-income industrial countries (Krausmann *et al.*, 2017). It also means that the higher the income, the more likely a household can afford the upfront costs of green technologies, which tend to be higher compared to conventional materials. The availability of disposable income after accounting for basic living expenses can significantly influence a household's ability to invest in sustainability. According to Owen *et al.*, (2018) financial capacity varies widely among households, with some managing to adopt sustainable technologies through government grants or financing programs despite lower income.

Access to Financing and Affordability

According to a research by Owen *et al.*, (2018), the various contexts of finance ecosystems are very local and regional, requiring public sector interventions that are sensitive to variances, particularly across higher and lower-income nations. Regulatory frameworks, geographic locations, and financial histories can all affect access to credit and incentives (Dabla-Norris *et al.*, 2015). This indicates that varying degrees of support are given for the adoption of sustainable materials and technology to the poor, medium, and upper classes. However, a study by Lorek and Spangenberg, (2014) found that there is a lack of clear understanding of the emerging challenges of sustainable practices in the era of scarcity and people became dependent on private funding, even though households can bridge this gap with incentives and subsidies offered by governments.

Educational Level and Awareness

Education plays a significant role in shaping behavioural intention, environmental knowledge, environmental sensitivity, environmental value, perceived behavioural control, and response efficacy (Wang *et al.*, 2018). This is because education not only helps people better understand environmental issues, but it also helps people realise their environmental responsibility. This indicates a positive correlation between education level and a greater comprehension of the economic and environmental advantages of implementing green technologies. More educated households are more proactive in seeking sustainable building solutions, whereas less educated households may have less access to knowledge or prioritise immediate financial needs over long-term environmental benefits.

Geographic Location and Housing Characteristics

Albert *et al.*,(2018) states that middle-income households tend to own their dwelling and in 2015, about 3 in every 4 (74%) middle-income households resided in dwellings that they own. Meanwhile, 23% rented, and 3% were informal settlers staying in a house or lot without the consent of the owner. In a 2017 study, Greyling and Tregenna analysed quality of life by region, primarily comparing income category, race, sex, age, and urban formal, informal, and tribal and farming communities. According to the report, 97% of White people live in formal housing, compared to 70% of African people, and 98% of White people have access to water on their property, compared to 63% of African people.

Stats SA shows that formal dwellings have 77.7% better living conditions. 75 % of the wealthier respondents reported being either satisfied or very satisfied with life while the low-income group selected the lack of income, high costs of living and a shortage of employment opportunities (Greyling and Tregenna, 2017). According to McLennan *et al.* (2016), people's first-hand experience of inequality is therefore contoured by the geographical settings in which they live, work, socialise and travel—making those renters or those in informal housing less likely to make such investments due to uncertainty over property rights or future residence. In Malaysia building projects that meet the green building index are given a property tax reduction (Agyekum *et al.*, 2022). This means that property owners generally have more freedom and incentive to invest in long-term upgrades such as solar panels, insulation, or eco-friendly materials.

Inequality in housing happens both inside and between demographic groups (Kährik and Pastak, 2023). Due to limited access to ownership, low-income groups particularly those from migrant and minority ethnic backgrounds are more likely to experience subpar housing and live in rental tenures. These disparities in affordability are especially noticeable for young people, low-income households, and private sector renters (Kährik and Pastak, 2023).This shows that all those in more permanent or higher-quality housing are usually more flexible in implementing sustainable practices because they want to invest in quality.

2.5.2. Impact of Socio-Economic Context in Classifying Households in South Africa

Low-Income Households in South Africa

Swilling et al. (2016) claim that South Africa is the world's most unequal society. The majority of low-income South Africans reside in low-cost RDP housing areas, which are primarily occupied by impoverished Black South Africans. According to Shackleton et al. (2018), the majority of the residents in these townships are impoverished Black South Africans who live in a mix of new and ancient housing. Due to poverty, individuals build homes using inexpensive or scavenged materials on abandoned property on the outskirts of towns or on empty land inside cities (Shackleton et al., 2018). In a similar vein, newly arrived migrants in South African towns typically take up vacant land, creating informal housing zones (Pauw et al., 2022). They do this in the hope of being allocated an RDP house (Makole *et al.*, 2022). This proves and shows that low-income housing adoption rates for sustainable materials are low affected by mostly high initial costs and most of the households depend on grants from the government for the cost of living.

Middle-income Households in South Africa

Swilling et al. (2016) claim that South Africa is the world's most unequal society. The majority of low-income South Africans reside in low-cost RDP housing areas, which are primarily occupied by impoverished Black South Africans. According to Shackleton et al. (2018), the majority of the residents in these townships are impoverished Black South Africans who live in a mix of new and ancient housing. Due to poverty, individuals build homes using inexpensive or scavenged materials on abandoned property on the outskirts of towns or on empty land inside cities (Shackleton et al., 2018). In a similar vein, newly arrived migrants in South African towns typically take up vacant land, creating informal housing zones (Pauw et al., 2022). Although the poor are most at risk of poverty in the future, the middle class is also at risk, thus the government must reevaluate its social protection programs and provide RDP homes and social housing for the middle class (Temidayo et al., 2018).

High-Income Households in South Africa

Shackleton *et al.* (2018) found that suburbs ranging from middle to high-income areas are occupied mostly by white South Africans, but now there is an increasing presence of other racial groups. Study by Ward and Shackleton (2016) states that wealthier urban households tend to have high-income-earning jobs, mostly measured by the number of assets and electricity spending. They are also associated with high levels of education, and these households are mostly located in the CBD and town areas of South Africa. According to Tetteh and Amponsah (2020), smart homes contribute to sustainable development. This implies that homeowners who choose smart housing are typically high-income earners who can afford the costs. They have the resources to fall back on alternative energy sources, such as generators and solar energy during load shedding, which people with low incomes cannot afford (Williams *et al.*, 2020). This means that high-income households have enough monetary value and knowledge to have a high adoption rate of sustainable materials.

Conceptual Framework Linking Socio-Economic Factors to Adoption Behaviour

Building on the factors discussed above, this study proposes a conceptual framework that illustrates how socio-economic context influences the adoption of sustainable building materials and technologies. The framework posits that socio-economic status (determined by income, education, and occupation) affects both **access** (to financing, information, and materials) and **motivation** (awareness, perceived benefits, and regulatory incentives). These, in turn, shape adoption behaviour. This model integrates the key variables identified in the literature and provides a structured basis for the empirical investigation in Cape Town.

In summary, the literature underscores that socio-economic factors, particularly income, education, and access to financing, are critical determinants of sustainable technology adoption. However, few studies have empirically compared these factors across income groups within a single, highly unequal urban context like Cape Town. This study builds on this gap by applying a structured socio-economic lens to adoption behaviour.

3. Materials And Methods

Both quantitative and qualitative data were gathered for this study using a mixed-methods approach. Similar studies have employed a quantitative method in isolation, this study attempts to investigate an alternative strategy to mitigate the drawbacks of doing so. A mixed-methods approach allows the study to retain the strengths of the two methods while mitigating the weaknesses each presents when used in isolation (Creswell and Poth, 2016). Mixed methods approach encourages the further refinement of the data beyond the results obtained by either qualitative or quantitative data on their own. It leads to a deeper understanding of the research problem that would not be achieved if a single method were used in isolation.

Figure 1 shows the steps of the research design and reveals that quantitative data were collected first through cross-sectional surveys, followed by qualitative data collection. It was analysed, and the results were used to collect the qualitative data through semi-structured interviews. It is from this compilation that the data presented in this investigation were derived, followed by the discussion, conclusion, and recommendation.

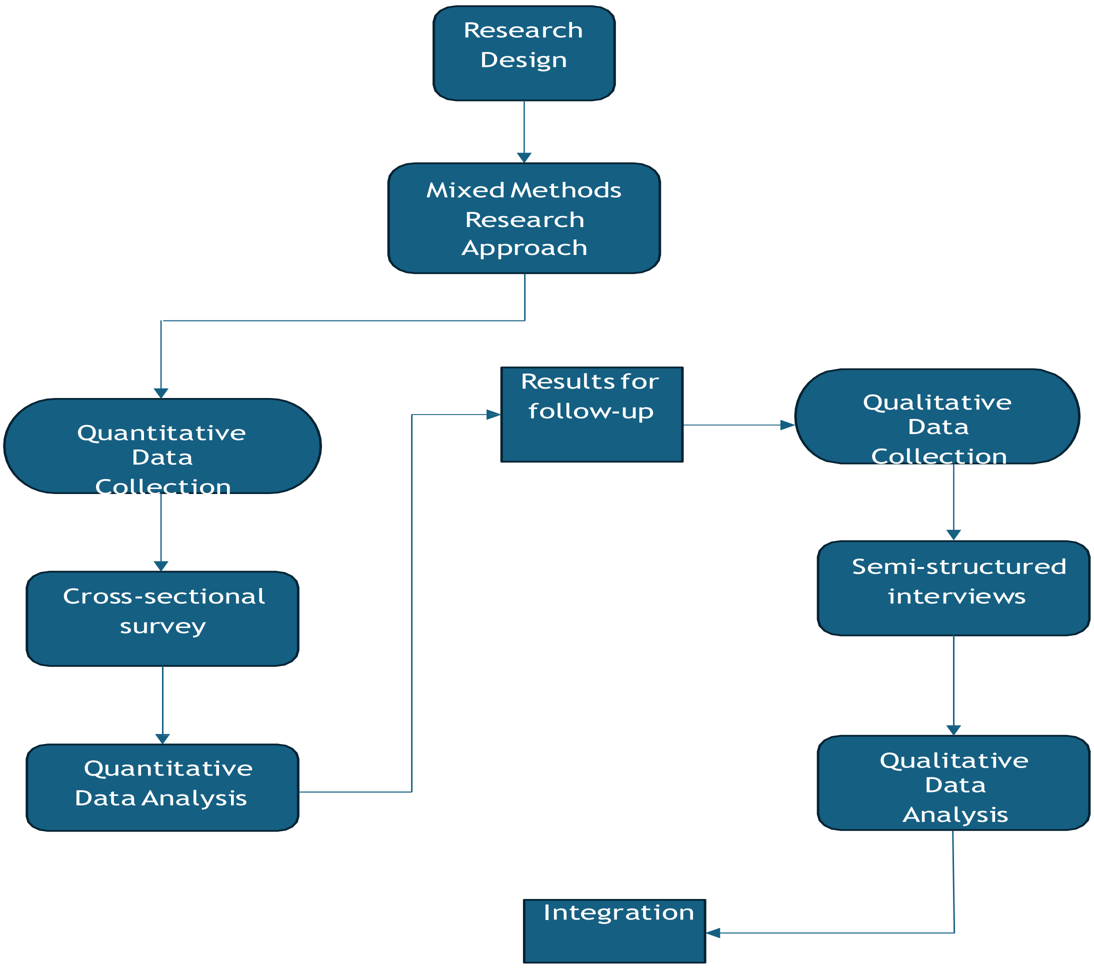

Figure 1: Research design and approach flow diagram

3.1. Population, Sampling Technique and Data Analysis Method

Residents of the Cape Town metropolitan region from a range of socio-economic backgrounds were the targeted group for the quantitative data and professionals working on the housing construction projects were the targeted population for the qualitative data. This investigation used probability and non-probability sampling techniques respectively to gather quantitative data and qualitative data.

As instrument, an online survey questionnaire and a probability-based method of sampling was used to allow statistical inference about data to be made (Andrews *et al.*, 2007). Random sampling ensured that all eligible participants had an equal chance of being selected for the study(68 respondents). Further, a purposive sampling technique was used for the semi-structured interviews process(15 experts). The rationale for using this technique was to mitigate bias and ensure reliability of the data while the geographical scope of the investigation covered Cape Town, South Africa. For the survey, a minimum sample of 30 per group (low-income and middle-high income) was used for comparative statistical analysis. The purposive sample of 15 experts ensured representation from key stakeholder groups (architects, contractors, policymakers) until thematic saturation was reached.
The data was analysed using three statistical methods: inferential, thematic, and descriptive statistical analysis. Descriptive statistics were employed to summarise the quantitative data. Conversely, inferential statistics drew conclusions using the sample statistics derived from descriptive statistics. Descriptive statistics were primarily used to characterise the data's measures of central tendency and dispersion. Lastly The NVivo software facilitated the identification, analysis, organisation, description, and reporting of themes in qualitative data through the use of thematic analysis.

Cronbach's alpha a numerical coefficient of reliability with a range between 0 and 1 where values of less than 0.3 are considered unreliable and should not be accepted while values of at least 0.7 suggests that the collected data is appropriate to be used for further analysis as it indicates high reliability. Consequently, the Cronbach's alpha of the survey questionnaire responses for this research scored 0.774, satisfying the condition.

3.2. *Ethical Considerations*

This study received ethical approval from the University of Cape Town's Ethics Committee. All participants provided informed consent prior to data collection. Survey responses were anonymised, and interview data were kept confidential. Participants were informed of their right to withdraw at any stage without penalty.

4. Findings and Discussion

4.1. *Participant Demographic Characteristics*

Table 1 below presents the demographic characteristics of respondents, including their level of education, employment status, income levels and home ownership status.

term environmental advantages. This was confirmed by Wang *et al.*, (2018) indicating that education plays a significant role in determining the development of behavioural intention, environmental knowledge, environmental sensitivity, environmental value, perceived behavioural control, and response efficacy. It is based on the fact that education not only helps people better understand environmental issues, but it also helps people realise their environmental responsibility.

4.2. *Location of respondents*

Table 2. below shows that 38.46% of respondents live in township, 38.46% from the suburban neighbourhood, 12.82% from the urban city centre, and 10.26% from the outskirts.

Table 1: Participant demographic characteristics

Race	**low-income Respondent**	**middle-high income Respondents**
Black	*89,66%*	*56,41%*
White	*3,45%*	*25,64%*
Colored	*6,90%*	*17,95%*
Education Level	**low-income Respondent**	**middle-high income Respondents**
High School	*75,86%*	*15,38%*
Bachelors	*10,34%*	*61,54%*
Master's Degree	*3,45%*	*2,56%*
Others	*10,34%*	*20,51%*
Employment Status	**low-income Respondent**	**middle-high income Respondents**
Employed Full-Time	*44,83%*	*87,18%*
Employed Part-Time (Retired)*	*24,14%*	*61,54%*
Unemployed	*17,24%*	*2,56%**
Students	*13,79%*	*5,13%*
Income Level	**low-income Respondent**	**middle-high income Respondents**
R0 to R54 344	*31,03%*	*0%*
R151 727 to R363 930	*68,97%*	*33,33%*
R363 931 to R631 120	-	*35,90%*
R631 121 to R863 906	-	*17,95%*
R863 907 to R1 392 844	-	*12,82%*
Home ownership status	**low-income Respondent**	**middle-high income Respondents**
Built my Own House	*32,14%*	*35,90%*
Bought an Existing Home	*7,14%*	*35,90%*
Rent	*46,43%*	*20,51%*
Other	*14,29%*	*7,69%*

Table 2: Location of Respondents

Outskirts	**Township**	**Urban City Centre**	**Suburban Neighborhood**
10,26%	*38,46%*	*12,82%*	*38,46%*

Table 1. above reveals that a there is positive relationship between education level and a comprehension of the economic and environmental advantages of sustainable building materials. The more educated the household, the greater the probability of being more proactive in seeking sustainable building solutions, whereas the less educated the household, the less likely it is to have access to knowledge or to prioritise immediate financial requirements over long-

Inequality in housing happens both inside and between demographic groupings. Due to limited access to ownership, low-income groups particularly those from migrant and minority ethnic backgrounds are more likely to experience subpar housing and live in rental tenures. These disparities in affordability are especially noticeable for young people, low-income households, and private sector renters (Kährik and Pastak, 2023).Those in more permanent or higher-quality housing are usually more flexible in implementing sustainable practices because they want to invest in quality.

4.3. *Nature of regulatory environment, Knowledge of sustainable building materials and Effect of sustainable building materials on reducing environmental impact*

According to Table 3, 23 out of 39 respondents in the middle-high incomeand 18 out of 29 respondents in the low-income categories indicated an informal regulatory environment. Overall, both the middle-incomeand upper-class groups mentioned an informal regulatory environment when it comes to the use of sustainable building materials. Additionally, 22 of the 29 respondents from the lower socio-economic classes were aware of sustainable building materials, while 39 of the middle-high school respondents, 34 were aware of sustainable building materials. In general, most respondents from both classes/groups were aware of sustainable building technology and materials. Lastly, the table reveals that 14 low-income respondents strongly agreed, 11 agreed, 2 were neutral, and 2 disputed that using sustainable building materials does assist lessen the environmental impact. It is logical to draw the conclusion that most respondents from both groups think that environmentally friendly building materials can have an effect on reducing environmental impact.

Table 3: Nature of regulatory environment, Knowledge of sustainable building materials and Effect of sustainable building materials on reducing environmental impact

Regulatory Environment	low-income Respondent	middle-high income Respondents
Informal	*18*	*23*
Formal	*11*	*16*
Knowledge of Sustainability	**low-income Respondent**	**middle-high income Respondents**
No	*7*	*5*
Yes	*22*	*34*
Effect on Reducing Environmental Impact	**low-income Respondent**	**middle-high income Respondents**
Strongly Disagree	-	-
Disagree	*2*	-
Neutral	*2*	*5*
Agree	*11*	*13*
Strongly Agree	*14*	*19*

Results indicate that government policies are important to some extent in fostering awareness of sustainable building materials, alongside incentives. Saha et al. (2021) found that regulatory frameworks on sustainable materials is still lacking in developing countries, and it still needs to be fostered. The study conducted by Luthra et al. (2015) with focused more on sustainable technology states that lack of public interest and litigation are among the barriers identified for promoting sustainable technologies. This shortfall in legal advocacy results in decreased motivation and lower public awareness. To solve this, government should engage more into clear labelling of energy usage on appliances, materials and machinery, along with certification to verify their energy-saving efficiency.

4.4. *Use of Sustainable building materials and Frequency of using sustainable materials*

Table 4 (See Appendix 1) reveals that 22 out of 39 respondents in the middle-high incomeand 16 out of 29 respondents in the low-income have never utilised solar panels. The findings indicate that although a sizable portion of both groups have used solar panels, the majority have not. Additionally, it reveals that whereas 31 out of 39 respondents from the middle-incomeand upper-class groups have not used green roofs, 24 out of 29 respondents from the lower-class group have not. They equally indicate that both respondent groups use green roofs relatively infrequently. When it comes to recycle materials, 22 out of 39 respondents in the middle-high incomeand 17 out of 29 respondents in the low-income had used them. Both groups utilise recycled materials more often than they do not. Finally, it reveals that although 23 of 39 respondents from the middle-high income group have used rainwater harvesting systems, 17 of 29 respondents from the low-income group have. Demonstrating that more people in both groups utilise rainwater harvesting systems than those who do not.

Regarding the affordability of sustainable building materials, over half of middle-income respondents considered them expensive or extremely expensive, and over half of respondents from lower socio-economic classes did the same. Both categories believe that sustainable building materials are more expensive than conventional ones.

The results are reflection of the change that is happening in South Africa construction industry as more people become aware of environmental issues and look for greener ways to build (Windapo, 2014). With problems like limited resources and climate change, the focus has shifted to materials that can help both the environment and the economy of the country(Korhonen *et al.*, 2018). Sustainable materials have the capacity of influencing how buildings are designed and built, offering a future where both the planet and people benefit (Raji *et al.*, 2015). Each alternative considered is setting new standards for eco-friendly construction, offering access to buildings that are better for the environment, affordable, and fit the growing demand for sustainable living (Korhonen *et al.*, 2018). Thus, shaping a more sustainable world.

These materials shouldn't only be durable but cost-effective and accessible to all for a low impact on the environment. Their versatility makes them great choices for various projects, from homes to commercial buildings. South Africa's commitment to sustainable development is clear in the increasing use of these innovative materials. They help reduce harmful emissions and promote a greener future, even though there are barriers to their adoption.

4.5. Factors influencing the adoption of Sustainable Materials

On the identification of the main variables influencing respondents' choices about the use of sustainable building materials, the RII scores of the factors for middle-incomeand low-income individuals are displayed in tables 5 and 6 below, respectively. The three most important aspects in low-income were initial cost, environmental effect, and long-term cost savings. The three variables that middle-incomeconsidered initial cost, environmental effect, and long-term cost savings revealing that variables influencing adoption in the middle-incomeand lower-class groups were the same.

As the study found, in some instances it costs more to embark on green building projects because green materials are mostly more expensive than their conventional counterparts. Construction cost comparison between 'green' and conventional office buildings prove that green building soft costs are higher than conventional projects due to incremental costs associated with the process of achieving a green building rating (Chan *et al.*, 2017). This involves both application costs as well as additional consulting required under the various rating tools. It is therefore necessary to avail financing options to encouraging the use of sustainable construction practices. Oguntona *et al.* (2019) corroborate with the findings of this investigation indicating that more financing alternatives, such as government incentives, can improve the implementation of green technologies.

Table 5: Influencing factors - low-income

Ranking	Influencing factors	RII
1	Cost saving in the long run	0,7
2	Initial cost	0,6
1	Environmental impact	0,7
2	Availability	0,6
3	Government incentives	0,5
2	Awareness and knowledge	0,6
2	Complying with building codes	0,6
2	Aesthetic appeal	0,6
2	Influence of media and adverts	0,6
2	Maintenance and ease of use	0,6

Table 6: Influencing Factors Middle-high class

Ranking	Influencing factors	RII
1	Cost saving in the long run	0,7
1	Initial cost	0,7
1	Environmental impact	0,7
2	Availability	0,6
3	Government incentives	0,5
1	Awareness and knowledge	0,7
2	Complying with building codes	0,6
2	Aesthetic appeal	0,6
3	Influence of media and adverts	0,5
1	Maintenance and ease of use	0,7

The findings of this study also demonstrate that environmental conditions have a major impact on the adoption of sustainable building materials. Along the same lines, Ahn et al. (2016) and Ngoy et al. (2023) confirmed that the need to mitigate climate change is one of the main environmental factors driving the adoption of sustainable practices, as building construction and operations significantly contribute to global greenhouse gas emissions.

5. Conclusion

This research aimed to evaluate the factors influencing the adoption of innovative sustainable building materials and technologies in housing construction across various socio-economic contexts. By investigating the relationship between socio-economic factors and the adoption of sustainable practices, the study provided valuable insights into the challenges and opportunities across different settings. The findings confirmed the hypothesis that there is a basic relationship between the adoption of sustainable materials and technologies and the socio-economic context. Key factors impacting adoption patterns include economic incentives, awareness and education, government policies, cultural values, and the availability of resources. The research highlighted significant differences in these factors based on socio-economic status, underscoring the need for targeted strategies that address the unique challenges faced by different communities. In conclusion, this study contributes to the understanding of how socio-economic contexts influence the adoption of sustainable building materials and technologies in housing construction. The insights gained can guide stakeholders such as policymakers, industry professionals, and community organisations in fostering more sustainable practices in the construction sector.

Acknowledgement
The authors acknowledge the support of the National Research Foundation (NRF) of South Africa, as well as the ARUA Mastercard–Carnegie Early Career Research Fellowship, which contributed to this research. The views and conclusions expressed in this paper are those of the authors and do not necessarily reflect those of the NRF, ARUA, or the Carnegie Corporation.

References

Abidin, N.Z. (2010). Investigating the awareness and application of the sustainable construction concept by Malaysian developers. *Habitat International*, **34**(4), 421-426. https://doi.org/10.1016/j.habitatint.2009.11.011

Afanasyeva, A., Fedorova, S. and Yulbarisova, G. (2020). Availability of innovative housing from the perspective of sustainable construction. *In IOP Conference Series: Materials Science and Engineering*. IOP Publishing, Vol. 890, 012182. https://doi.org/10.1088/1757-899x/890/1/012182

Agyekum, K., Goodier, C. and Oppon, J.A. (2022). Key drivers for green building project financing in Ghana. *Engineering, Construction and Architectural Management*, **2G**(8), 3023-3050. https://doi.org/10.1108/ecam-02-2021-0131

Ahn, Y.H., Jung, C.W., Suh, M. and Jeon, M.H. (2016). Integrated construction process for green building. *Procedia engineering*, **145**, 670-676. https://doi.org/10.1016/j.proeng.2016.04.065

Alabi, B. and Fapohunda, J. (2021). Effects of increase in the cost of building materials on the delivery of affordable housing in South Africa. *Sustainability*, 13(4), 1772. https://doi.org/10.3390/su13041772

Albert, J.R.G., Santos, A.G.F., & Vizmanos, J.F.V. (2018). Defining and profiling the middle class in the Philippines. Philippine Journal of Development, 45(1), 1-30.

AlSanad, S. (2015). Awareness, drivers, actions, and barriers of sustainable construction in Kuwait. *Procedia engineering*, 118, 969-983. https://doi.org/10.3390/su13041772

Andrews, D., Nonnecke, B. and Preece, J. (2007) Conducting research on the internet:: Online survey design, development and implementation guidelines. *Annual Review of environment and resources*, **42**(1), 647-675.

Baker, E.H. (2014) Socio-economic status, definition. *The Wiley Blackwell encyclopedia of health, illness, behaviour, and society*, 2210-2214. behaviors: a survey of the rural residents in China. *Journal of Cleaner Production*, 63, 152-165. https://doi.org/10.1002/9781118410868.wbehibs395

Bornstein, M.H. and Bradley, R.H. (2014) *Socio-economic status, parenting, and child development*. Routledge.buildings in Tanzania: a qualitative case study. *International Journal of Building Pathology and Adaptation*. https://doi.org/10.4324/9781410607027

Cao, Y., Xu, C., Kamaruzzaman, S.N. and Aziz, N.M. (2022) A Systematic Review of Green Building Development in China: Advantages, Challenges and Future Directions. *Sustainability*, **14**(19). https://doi.org/10.3390/su141912293

Chan, A.P.C., Darko, A., Ameyaw, E.E. and Owusu-Manu, D.-G. (2017) Barriers Affecting the Adoption of Green Building Technologies. *Journal of Management in Engineering*, 33(3). https://doi.org/10.1061/(asce)me.. 1943-5479.0000507

Dabla-Norris, M.E., Ji, Y., Townsend, R. and Unsal, M.F. (2015). *Identifying constraints to financial inclusion and their impact on GDP and inequality: A structural framework for policy*. International Monetary Fund. https://doi.org/10.5089/9781498381598.001

Dosumu, O. and Aigbavboa, C. (2018) *Sustainable design and construction in Africa: a system dynamics approach*. Routledge. https://doi.org/10.1201/9781351212205

Eizenberg, E. and Jabareen, Y. (2017).Social sustainability: A new conceptual framework. *Sustainability*, **G**(1), 68. https://doi.org/10.3390/su9010068

Eze, E.C., Sofolahan, O. and Omoboye, O.G. (2023) Assessment of barriers to theadoption of sustainable building materials (SBM) in the construction industry of a developing country. *Frontiers in Engineering and Built Environment*, 3(3), 153- 166. https://doi.org/10.1108/febe-07-2022-0029

Eze, E.C., Ugulu, R.A., Onyeagam, O.P. and Adegboyega, D.A. (2021). Determinants of sustainable building materials (SBM) selection on construction projects. https://doi.org/10.14424/ijcscm110221-166-194

Gohari, A., Gohari, A., Ahmad, A.B., Mokhtar, K., Oloruntobi, O., Johari, N.H. and Darwin, N.B. (2024) Multi-criteria analysis of barriers to the use of green building technologies in residential buildings: a case study of Mashhad, Iran. *Clean Technologies and Environmental Policy*. https://doi.org/10.1007/s10098-024-02920-0

Greyling, T. and Tregenna, F. (2017) Construction and analysis of a composite quality of life index for a region of South Africa. *Social Indicators Research*, **131**, 887-930. https://doi.org/10.1007/s11205-016-1294-5

Huang, W.-H. (2015). The determinants of household electricity consumption in Taiwan: Evidence from quantile regression. *Energy*, 87, 120-133. https://doi.org/10.1016/j.energy.2015.04.101

Javaid, M., Haleem, A., Singh, R.P., Suman, R. and Gonzalez, E.S. (2022) Understanding the adoption of Industry 4.0 technologies in improving environmental https://doi.org/10.1016/j.susoc.2022.01.008

Kährik, A. and Pastak, I. (2023). Access to homeownership in decline—rising housing inequalities for young people in the neoliberal housing market of Tallinn. *Frontiers in Sustainable Cities*, 5, 1149087.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havranek, M., Pataki, D., Phdungsilp, A., Ramaswami, A. and Mendez, G.V. (2009) Greenhouse gas emissions from global cities. In: ACS Publications. https://doi.org/10.1021/es900213p

Khalid Mehmood Sadar, D. and Ishak, M.S. (2024) Sustainable Building Construction Materials in the United Arab Emirates: A Review. *Sustainability*, 16(15), 6565. https://doi.org/10.3390/su16156565

Khan, R.A., Liew, M.S. and Ghazali, Z.B. (2014) Malaysian construction sector and Malaysia vision 2020: Developed nation status. *Procedia-Social and Behavioural Sciences*, **10G**, 507-513.

Khudzari, F., Rahman, R. and Ayer, S. (2021) Factors Affecting the Adoption of Emerging Technologies in the Malaysian Construction Industry. *In*, *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, Vol. 641, 012006.

Korhonen, J., Honkasalo, A. and Seppälä, J. (2018) Circular economy: the concept and its limitations. *Ecological economics*, 143, 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S. and Jackson, T. (2017) Material flow accounting: measuring global material use for sustainable development. https://doi.org/10.1146/annurev-environ-102016-060726

Lorek, S. and Spangenberg, J.H. (2014) Sustainable consumption within a sustainable economy–beyond green growth and green economies. *Journal of Cleaner Production*, **63**, 33-44.

Luthra, S., Kumar, S., Garg, D. and Haleem, A. (2015) Barriers to renewable/sustainable energy technologies adoption: Indian perspective. *Renewable and sustainable energy reviews*, 41, 762-776. https://doi.org/10.1016/j.rser.2014.08.077

Makole, K.R., Ntshangase, B.A., Maringa, M.S. and Msosa, S.K. (2022). Can a basic income grant improve the quality of life for the poor in South Africa: An analytical review. *Business Ethics and Leadership*, 6(3), 57-67. https://doi.org/10.21272/bel.6(3).57-67.2022

Marsh, R., Brent, A. and De Kock, I. (2020) An integrative review of the potential barriers to and drivers of adopting and implementing sustainable construction in South Africa. *South African Journal of Industrial Engineering*, 31(3), 24-35.

McLennan, D., Noble, M. and Wright, G. (2016) Developing a spatial measure of exposure to socio-economic inequality in South Africa. *South African* https://doi.org/10.1080/03736245.2015.1028980

Moghayedi, A., Awuzie, B., Omotayo, T., Le Jeune, K. and Massyn, M. (2022) Appraising the nexus between influencers and sustainability-oriented innovation adoption in affordable housing projects. *Sustainable Development*, **30**(5), 1117-1134. https://doi.org/10.1002/sd.2306

Mushi, F. V., Nguluma, H., & Kihila, J. (2023). Factors influencing adoption of green buildings in Tanzania: a qualitative case study. International Journal of Building Pathology and Adaptation. https://doi.org/10.1108/ijbpa-11-2022-0173

Ngoy, K.S., Chisumbe, S., Petere, G., Mwiya, B., & Mwanaumo, E. (2023). Factors influencing professional indemnity insurance use in construction risk management. *Baltic Journal of Real Estate Economics and Construction Management*, *11*(1) 199–220. https://doi.org/10.2478/bjreecm-2023-0013

Oguntona, O.A., Akinradewo, O.I., Ramorwalo, D.L., Aigbavboa, C.O. and Thwala, W.D. (2019). Benefits and Drivers of Implementing Green Building Projects in South Africa. *Journal of Physics: Conference Series*, 1378(3).

Okitasari, M., Mishra, R. and Suzuki, M. (2022) Socio-Economic Drivers of Community Acceptance of Sustainable Social Housing: Evidence from Mumbai. *Sustainability*, 14(15). https://doi.org/10.3390/su14159321

Okogwu, C., Agho, M.O., Adeyinka, M.A., Odulaja, B.A., Eyo-Udo, N.L., Daraojimba, C. and Banso, A.A. (2023) Exploring the integration of sustainable materials in supply chain management for environmental impact. *Engineering Science & Technology Journal*, **4**(3), 49-65.

Owen, R., Brennan, G. and Lyon, F. (2018) Enabling investment for the transition to a low carbon economy: Government policy to finance early stage green innovation. https://doi.org/10.1016/j.cosust.2018.03.004

Pauw, C.J., Montagu Murray, H. and Howard, M.A. (2022) The use of dirty fuels by low- income households on the South African Highveld. *Clean Air Journal*, 32(1), 1-17. https://doi.org/10.17159/caj/2022/32/1.12508

Purvis, B., Mao, Y. and Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability science*, 14, 681-695.

Raji, B., Tenpierik, M.J. and Van Den Dobbelsteen, A. (2015). The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*, 45, 610-623. https://doi.org/10.1016/j.rser.2015.02.011

Saha, S., Hiremath, R.B., Prasad, S. and Kumar, B. (2021) Barriers to Adoption of Commercial Green Buildings in India: A Review. *Journal of Infrastructure Development*, 13(2), 107-128. https://doi.org/10.1177/09749306211058499

Shackleton, C., Blair, A., De Lacy, P., Kaoma, H., Mugwagwa, N., Dalu, M. and Walton, W. (2018) How important is green infrastructure in small and medium-sized towns? Lessons from South Africa. *Landscape and Urban Planning*, 180, 273- 281. https://doi.org/10.1016/j.landurbplan.2016.12.007

Shama, Z.S. and Motlak, J.B. (2019) Indicators for Sustainable housing. *In*, *IOP conference series: materials science and engineering*. IOP Publishing, Vol. 518, 022009.

Swilling, M., Musango, J. and Wakeford, J. (2016) Developmental states and sustainability transitions: prospects of a just transition in South Africa. *Journal of Environmental Policy & Planning*, 18(5), 650-672. https://doi.org/10.1080/1523908x.2015.1107716

Temidayo, O., Aigbavboa, C., Oke, A. and Ohiomah, I. (2018) Construction 4.0: towards delivering of sustainable houses in South Africa. *In Creative Construction Conference 2018*, 147-156. https://doi.org/10.3311/ccc2018-020

Tetteh, N. and Amponsah, O. (2020) Sustainable adoption of smart homes from the Sub-Saharan African perspective. *Sustainable Cities and Society*, 63, 102434.

Turcotte, D.A. and Geiser, K. (2015) A Framework to Guide Sustainable Housing Development. *Housing and Society*, 37(2), 87-117. https://doi.org/10.1080/08882746.2010.11430582

Wang, P., Liu, Q., & Qi, Y. (2014). Factors influencing sustainable consumption behaviors: a survey of the rural residents in China. Journal of Cleaner Production, 63, 152–165. https://doi.org/10.1016/j.jclepro.2013.05.007

Ward, C.D. and Shackleton, C.M. (2016) Natural resource use, incomes, and poverty along the rural–urban continuum of two medium-sized, South African towns. *World Development*, 78, 80-93.

Weilenmann, B., Seidl, I. and Schulz, T. (2017) The socio-economic determinants of urban sprawl between 1980 and 2010 in Switzerland. *Landscape and Urban Planning*, **157**, 468-482. https://doi.org/10.1016/j.landurbplan.2016.08.002

Williams, S.P., Thondhlana, G. and Kua, H.W. (2020) Electricity use behaviour in a high-income neighbourhood in Johannesburg, South Africa. *Sustainability*, 12(11), 4571. https://doi.org/10.3390/su12114571

Windapo, A.O. (2014) Examination of green building drivers in the South African https://doi.org/10.3390/su6096088

Appendix 1

Table 4: Use of Sustainable building materials and Frequency of using sustainable materials

Sustainable Building Material		low-income Respondent	middle-high income Respondents
use of solar panels	*Yes*	*13*	*17*
	No	*16*	*22*
use of recycled materials	*Yes*	*12*	*22*
	No	*17*	*17*
use of green roofs	*Yes*	*5*	*8*
	No	*24*	*31*
Use of rainwater harvest	*Yes*	*12*	*23*
	No	*17*	*16*
Frequency of using sustainable materials			
Always		*2*	*2*
Frequently		*6*	*8*
Occassionally		*11*	*16*
Rarely		*7*	*10*
Never		*3*	*3*
Affordability of sustainable building materials			
Very Affordable		*4*	*5*
Affordable		*10*	*8*
They are the same		*3*	*5*
Expensive		*11*	*18*
Very Expensive		*1*	*3*